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Statistical Analysis Of Groundwater Use And Replenishment

J. D. Rockaway

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STATISTICAL ANALYSIS OF GROUND WATER USE AND REPLENISHMENT

by

J. D. Rockaway

R. B. Johnson

September 1967

PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
LAFAYETTE, INDIANA

STATISTICAL ANALYSIS OF GROUND WATER
USE AND REPLENISHMENT

by

J. D. Rockaway
R. B. Johnson

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ABSTRACT

The value of ground water as a natural resource is becoming more apparent as demands for water increase with growing population and industrialization. Ground water investigations are an integral part of urban and industrial planning and new techniques continually are being developed to facilitate these investigations.

As ground water research is accelerated and basic data on aquifer parameters are more abundant, a statistical approach to the evaluation of the ground water regimen becomes increasingly useful. One such statistical technique that offers considerable potential is the fitting of polynomial trend-surfaces to ground water data, and studying the variations in the surfaces and the residuals from these surfaces over a period of time.

A trend-surface analysis of hydrogeologic data was carried out in an attempt to derive techniques which could give additional guidance in the selection of areas suitable for the development of future ground water resources. South Bend, Indiana was selected as an area of maximum municipal and industrial ground water requirements and Bartholomew County, Indiana was chosen as an area of essentially rural or small-scale demands. Both of these areas obtain their water supplies from sand and gravel aquifers of glacial origin in which water levels have been monitored over a period of several years.

Trend-surface maps and maps of the residuals from the trend surfaces were prepared from the water-level data at regular intervals and evaluated to establish their relationships with the hydrogeologic regimen. The maps were compared with conventional water-table or piezometric maps drawn from the same data, with known subsurface conditions and aquifer parameters, and the fluctuations of these maps with time were compared with variations in the recharge and discharge characteristics of the ground water reservoir.

A field-testing program was carried out in Bartholomew County to evaluate the hydrogeologic parameters of an area determined by the trend-surface analysis to be favorable for the development of ground water resources.

On the basis of the results obtained from these studies, the following conclusions were drawn:

1. A mathematically computed surface may be considered to approximate the water-table or piezometric surface. This surface will be sensitive to variations in recharge and discharge as they influence the ground water reservoir.
2. The addition of orthogonal flow lines to the contours of the trend-surface maps can provide additional information on the direction and relative amounts of ground water flow.
3. The anomalous areas of the trend-surface or residual maps represent local effects superimposed on the regional base and may be explained by a particular set of geologic, hydrologic or man-made conditions.
4. Wells from a multiple aquifer system or from an aquifer not associated with the aquifer under study may be identified from the given population of wells.
5. The trend-surface approach to the analysis of ground water levels cannot be completely successful unless the requirements for suitable data are satisfied.

INTRODUCTION

Background

As the ever increasing demands for water increase with growing population and industrialization, an awareness of the value of this natural resource also grows. In recent years ground water has accounted for somewhere between one-fifth and one-sixth of the nations total use of water, which was about 170 billion gallons per day (gpd) in 1950, 270 billion gpd in 1960 and is estimated by the Senate Select Committee on National Water Resources to be 559 billion gpd in 1980 and 888 billion gpd by the year 2000. As the total demand increases, the fraction taken from the ground may go up or down or remain about the same, but absolute withdrawal of ground water cannot help increasing. Because of the increasingly important role ground water is playing in national development, substantial advances in the understanding of the ground water regimen have been achieved during the past decade. New techniques of ground water study are continually being developed as water resource investigations become more and more critical.

A ground water study requires the definition of the geological model in which the water occurs and through which it moves on two scales:

1. The regional hydrogeologic environment and the identification of aquifers within this framework.

2. The individual well-site locations within the aquifer where wells may be most economically situated.

Geology may be most readily and beneficially applied to the studying of the regional ground water environment because as a tool it is most suited to the generalized study of conditions over large areas. Geologic methods are most difficult to apply to the location of specific well sites where geologic details determine the economic success of the well.

The problem of predicting areas for potential ground water development involves a controlled search for a specific set of geologic conditions which may be located anywhere with an area defined by the established economic boundaries. This approach is in contrast to a subsurface engineering investigation which involves the careful assessment of the variation in engineering properties of the materials encountered at a particular site, the location of which is restricted by other conditions. The foundation engineer must design the foundation for a structure to accomodate the geologic details that he encounters during exploration, while the ground water geologist must search throughout an area for the geologic environment that is required to satisfy the desired yield.

Current research is directed toward an effort to provide the ground water geologist with more comprehensive techniques of quantifying the ground water regimen and of extracting the maximum amount of information from available data. Much of

this research is centered about the construction of mathematical or electrical analog models. It is often possible to simulate aquifer conditions with analytical or numerical solutions to the mathematical models in which problems associated with the complex geohydrologic boundaries are simplified by a particular set of assumptions. Geohydrologic settings in many areas too complex to permit quantitative description with analytical expressions have been analyzed in some instances by an electric analog model. Such models directly simulate the geometry and hydraulic characteristics of the water bearing materials which form the ground water system and can play an important role in the forecasting of the consequences of developing nonhomogeneous aquifers.

As groundwater research is accelerated and basic data on aquifer parameters becomes more abundant, a statistical approach to the evaluation of the ground water regimen becomes increasingly useful. One such statistical technique which, although not proven, offers considerable potential is now feasible with readily available high-speed computers. This technique is the fitting of polynomial trend-surfaces to ground water data and studying the variations in the surfaces and the residuals from these surfaces over a period of time.

The usefulness of trend-surface analysis in solving geologic problems has been documented by many studies. Important early works were those of Miller (1956) and Krumbein (1950, 1959).

Many of the investigations that followed dealt with the trend surface analysis of petrologic or facies data (Whitten, 1959, Allen and Krumbein, 1962), although the application of trend-surfaces to structural data was illustrated by Wolfe (1962) and Merriam (1964). The interested reader is referred to Krumbein and Graybill (1965) for a discussion of the development of trend-surface techniques and a comprehensive bibliography of the application of trend-surface analysis in the geologic sciences.

Hydrogeologic data have many similarities with petrologic and structural data. They represent the combined effect of regional and local influences that have been measured from spatially distributed control points. The success of structural and petrologic trend-surface analysis suggests that a trend-surface approach to hydrogeologic data should provide additional insight into conditions governing the ground water regimen.

Unfortunately, the analysis of trend-surface maps has not progressed to the stage of quantified comparison but is dependent on visual comparison and subjective pattern recognition, although considerable effort is now being directed toward pattern discernment and interpretation (Spitz, 1966). The trend-surface approach does, however, provide the opportunity to remove the regional hydrogeologic framework, thus amplifying or reinforcing the local component to make it more conspicuous.

This type of analysis does not reveal features that cannot be perceived in the original data by close examination. What it does do is accentuate areas of less than regional magnitude to bring out details of the ground water regimen. The specific hydrogeologic parameters of these areas so delineated may then be studied in detail provided sufficient hydrogeologic data are available.

Johnson and Goodell (1963) investigated the ground water dynamics of the Floridan aquifer by fitting polynomial surfaces to the water levels measured during the study period, contending that the computed surface was representative of the actual piezometric surface. The output from the program contained the predicted water levels for each power surface as well as the residual values between the predicted and the observed levels. They found that fluctuations in the regional trend-surface could be related to seasonal and long-term variations in discharge and recharge, and that the residuals were functions of permanent recharge and discharge sites and/or geological factors which affect ground water movement.

The trend-surface techniques used in this present study were based on those developed in the work discussed in the unpublished report by Johnson and Goodell (1963). These procedures and the refinements made on them formed the basis for the studies in this project and are discussed in the description of the research approach.

Statement of Research Problem

The Office of Water Resources Research, the funding agency for this study, has designated this research as "Statistical Analysis of Ground Water Use and Replenishment." The objective of this project was a better understanding of the relationships existing among geologic conditions, natural discharge and recharge rates, and municipal and industrial use rates. It was anticipated that this objective would be fulfilled through the development of a trend-surface analysis of ground water levels. This understanding hopefully would permit prediction of future conditions based on established trends in precipitation and water use as well as assisting in the location of favorable sites for development of ground water use facilities. The study had as a goal the establishment and prediction of areas which could or could not support greater industrial and urban growth.

The investigation was limited to the study of two areas; namely, one of minimum municipal and industrial ground water use and one of extensive ground water use. It was also proposed that only glaciated areas be selected. This eliminated consideration of bedrock aquifers, but did not eliminate aquifers such as outwash material which may be considered to have been derived from glaciation.

A research plan was drawn up at the beginning of the investigation and a variety of individual problems, all of which

contribute to the overall objective, were selected for study. A few of those problems were: the separation of areas of extensive discharge and recharge from the trend maps; the correlation of water levels with short- and long-term rainfall to serve as a guide to water use rates; the study of the lag in the effect of seasonal pumping rates on well water levels as a guide to determining the transmissibility of the water-bearing materials; the location of multiple aquifer producing wells based on the anomalies of the trend maps; determining the relationships existing between known geologic conditions such as aquifer thickness, porosity, and lateral extent and ground water levels and pumping rates; and the computation of orthogonal flow lines to trend map contours for the determination of ground water flow directions and quantities.

The individual problems were investigated by standard statistical methods. Selection of data collection sites were of necessity biased because of the limited number of wells and the obvious bias inherent in the selection of drilling sites. Every effort was made to conduct each individual problem so that maximum reliability could be attached to the results within the limits imposed by the data.

RESEARCH APPROACH

Requirements

The first step of the research program was the selection of two areas for study, one area of minimum municipal and industrial ground water use and one of extensive ground water use. As a further restriction, the ground water was to be obtained from aquifers of glacial origin. A requirement in each case was the availability of long term data for precipitation, pumping rates, and ground water levels taken at regular, relatively short intervals.

The statistical procedure of investigation, which was to be the basis of this project imposed several restrictions in addition to the geological requirements which were to be satisfied. It was necessary that there be sufficient data points, in this case observation wells, so that the F-test used to evaluate the goodness of fit of the polynomial surfaces would be meaningful. Also, the observation wells had to be located close enough together so that the data would be representative of the areas between wells, and, at the same time, it was necessary that a limited number of wells fully cover the extent of the aquifer under investigation. As water wells are almost always drilled in locations which appear to be most favorable for water production, it was not feasible to consider the data points to be randomly scattered over the study area.

Accumulation of Data

The South Bend-Mishawaka metropolitan region in central St. Joseph County, Indiana (Figure 1), was chosen to fill the requirement for an area of heavy ground water demand because of the availability of data accumulated as a result of an extensive study by the U. S. Geological Survey (Klaer and Stallman, 1948) published by the Indiana Department of Conservation. A one-year period, 1945, was selected during which the maximum amount of data was recorded. Monthly water-level readings were available from 18 non-pumping wells established for this survey. Daily precipitation data were obtained from the records of three recording stations maintained in the greater South Bend area. Rates and amounts of ground water pumped by the South Bend Water Company were supplied from company files.

Central Bartholomew County, Indiana (Figure 1), was selected for the area of minimum ground water use. The ground water resources of Bartholomew County were being investigated by a cooperative effort of the Indiana Department of Conservation, Division of Water Resources, and the U. S. Geological Survey during the time this study was in progress and data from this investigation were available. Thirty-three observation wells had been established from which ground water levels were determined at monthly increments. Precipitation data was obtained from U. S. Weather Bureau records and pumping data from the

FIGURE 1. MAP OF INDIANA SHOWING AREAS OF INVESTIGATION.

Columbus Utilities Board. A two-year period, April 1965 to April 1967, was chosen to coincide with the investigation being carried out by the government agencies.

Analysis of Data

Analysis of the data accumulated for each region was divided into three phases each based on variation with time; analysis of recharge and discharge data and characteristics; analysis of ground water levels by a trend-surface technique; and, a comparison of the variation of recharge and discharge with fluctuations in the trend surfaces computed from the water level data.

The precipitation of each area was taken to be the average of the monthly amounts recorded at the separate stations during the study period. This average value was plotted versus time on a monthly basis. The graphs produced in this manner were subject to a great deal of fluctuation, but were considered more useful than the smoother graphs produced using the mean monthly precipitation averaged over the preceeding years. Although recharge to the aquifer was not limited to precipitation, it was not feasible to attempt to evaluate the amount of recharge that was taking place through ground water flow or stream inflow, and recharge by these methods was presumed to have remained essentially constant.

Discharge through pumping was treated in a similar manner. The amount of water withdrawn from the ground water reservoir was plotted on a monthly basis. Data from the municipal well fields were more complete and accurate than the data from private or industrial wells. Records of non-municipal pumping, where available, indicated that it was proportional to the municipal pumping throughout the year, thus the records of municipal pumping were considered satisfactory to represent fluctuations in rates of ground water withdrawal. As with the evaluation of recharge data, discharge through ground water flow could not be estimated.

The application of trend-surface analysis to this study was based on the premise that the piezometric surface or water-table was approximated by a mathematically computed polynomial surface of the water levels of the wells in the aquifer. These plane or gently curving surfaces, fitted by the least square method, represent general or regional changes in the measured data. A surface is described by an equation in which a dependent variable, water level, is a function of two independent location variables. The trend surface analysis consists of fitting a polynomial surface to the observed data up to a degree such that the systematic change is adequately specified. This essentially divides the data into two or more parts, one part associated with the large-scale changes established for the study area, and others associated with localized changes super-

imposed on the regional pattern.

The superimposed effects were delineated by the residuals from the trend or regional surface. Removal of the trend, leaving only the residuals has the property of amplifying or reinforcing the local component and making it more conspicuous. Trend-surface analysis does not reveal features that cannot be perceived in the regional data; however, trend-surface analysis does strongly accentuate features that are of less than regional magnitude, thereby bringing out details that may have gone unnoticed.

The location of each observation well on an arbitrarily assigned grid was determined and monthly water level readings placed on computer cards for each location. A polynomial trend-surface program was employed permitting the mathematical fitting of surfaces from the linear, or first power to quintic, or fifth power, with F-ratio print-out data available for determining the best surface fit. Output from the program contained predicted water levels for each power surface as well as the residual values at each well location. The residual was defined as the difference between the actual water level and the predicted or computed level, and was considered positive when the actual value exceeded the predicted value. A grid computing program was then employed to grid the scattered data into a form acceptable for a Calcomp plotting routine. Contour maps of the trend-surfaces as well as contour maps of the residuals were prepared.

Changing elevations and gradients of contour lines drawn on the computed surfaces indicated regional changes in the ground water reservoir and corresponded with a raising or lowering of the water levels in the aquifer. Orthogonal flow lines drawn perpendicular to these contour lines illustrated the direction of ground water flow. Changes in the gradients and azimuths of the surfaces with time more specifically represent their sensitivity to fluctuations in discharge or recharge. The gradients and azimuths of the linear surfaces were most convenient to work with in this type of analysis as they could be determined in a uniform manner and represented variation in the surface orientation as well as did the same features of the higher power surfaces. For each month of the test period, these values were plotted and the resulting graph compared with those of discharge and recharge to determine what relationships, if any, existed between them.

The residuals from the trend surfaces supplied by the program printout were examined to find out if there was any correlation between their values and the hydrogeologic parameters such as thickness, lateral extent and permeability of the aquifers underlying the study areas. The residuals from each trend surface, the mean quadratic residual over the study period, and the standard deviation from this mean value were plotted at each well location and contoured. The residuals from the quadratic surface were chosen for this phase of the study because they

adequately represented the local components without being subjected to a great amount of influence by the mathematical surface.

Two assumptions regarding the nature of the residuals were necessary if they were to be useful for aquifer analysis. The residuals must be uncorrelated and their average value should be zero. When the observations are taken independently of each other the assumption that the residuals are uncorrelated is usually fulfilled. If the method of water level measurement is free from bias or systematic error and the nature of the water levels such that positive and negative values have the same likelihood of occurrence, then the average values of the residuals may be assumed to be zero and the second assumption fulfilled.

It was expected that approximately one-half of the residuals would be positive and one-half negative. If the hydrogeologic parameters of the area were generally homogeneous, these values would be distributed over the area on a random basis, subject to very local variations, and the pattern of distribution would illustrate no segregation of values. Non-homogeneity would be indicated by grouping of residuals of like sign or particularly large values of selected residuals. In a ground water investigation, this non-homogeneity is related to the ground water regimen. An area in which either positive or negative residuals predominate, remaining essentially in the same vicinity while the

trend surface fluctuates with seasonal variation, represents an anomaly that must be explained by the hydrogeologic conditions. Likewise, a particularly high value of a residual, greater than two or three standard deviations from the mean residual, required a singular explanation. By contouring the residuals, these areas were delineated for further study. The contoured surface of the residuals from the quadratic trend surface prepared for each month provided insight into the relative geographic stability of anomalous areas. Those areas resulting from distinctive features of the hydrogeologic parameters, remained essentially in the same position as other factors changed.

The standard deviations of the mean residuals at each well location are related to fluctuations of water levels. Greatly fluctuating water levels yield relatively high values for the standard deviation. The standard deviations, plotted at each well location and contoured, indicated areas of maximum and minimum ground water fluctuation with time. Hence, like the residuals themselves, the standard deviations were used to delineate areas of anomalous hydrogeologic conditions or response to recharge and discharge.

As a measure of the overall sensitivity of the aquifer to seasonal variation, the mean value of the standard deviations of the individual wells was determined at monthly increments.

This value was plotted for the extent of the test period and the resulting graph compared with the graphs of recharge and discharge for possible relationships.

The evaluation of the applicability of trend surface analysis to ground water investigations in glacial aquifers was essentially made up of two considerations. One phase was concerned with the relationship that existed between the trend surfaces and the actual ground water levels as represented by the piezometric or water table surface. This included investigation of the sensitivity of the surfaces to fluctuations in recharge and discharge to determine if the trend-surfaces adequately approximated the form and action of the water level surface. The other phase involved a study of the potential use of the residuals from the trend-surfaces to assist in the location of favorable sites for future development of ground water resources or sites of over-exploitation of water resources.

To accomplish this evaluation, the stratigraphy and geological characteristics of each site was established from previous studies of the areas and applied with the data provided from the trend-surface analysis for a detailed examination of aquifer parameters. A variety of individual problems were examined, all of which contributed to the main problem of water resource evaluation. Areas of excessive recharge or discharge were located and their relationship with known hydrogeologic conditions established. Fluctuations in water level were correlated with variations in recharge and discharge and the

effects of seasonal pumping rates or natural recharge used as a guide for determining the transmissibility of the water bearing formations. Also, the directions and amounts of ground water flow were estimated by the construction of orthogonal flow lines to trend surface contours. As a conclusion to the investigation, an attempt was made to select an area best suited for potential development of ground water use facilities.

Upon completion of the study of each area, the conclusions on aquifer behavior drawn from this study were compared with the conclusions drawn from a standard ground water survey of the same area. This comparison was facilitated by the comprehensive report of the South Bend Region and the current study of Bartholomew County being undertaken, on a cooperative basis, by the U. S. Geological Survey and the Indiana Department of Conservation, Water Resources Division. These comparisons provided the basis for the critical examination of the application of trend-surface analysis in ground water investigations. They served to illustrate the advantages that a statistical procedure offers and at the same time, emphasized the limitations and restrictions that must be considered with an approach of this type, namely, the need for numerous data points and time interval data collection.

SOUTH BEND INVESTIGATION

Description of Area

The South Bend-Mishawaka metropolitan region is located in St. Joseph County in northern Indiana, about 5 miles south of the Indiana-Michigan state line (Fig. 1). The population, according to U. S. Census Bureau figures was 132,000 in 1960 and approximately 125,000 in 1945 during the study period. This is a heavily industrialized area, particularly so during these years.

The climate is typical of northern Indiana and southern Michigan. The average annual precipitation is about 35 inches according to U. S. Weather Bureau Records, and well distributed throughout the year. The heaviest rainfall generally occurs during May, when conditions for ground water recharge are especially favorable.

Physiography

Northern Indiana is placed by Fenneman (1931) in the Great Lakes Section of the Central Lowlands Physiographic Province. This section is characterized by a variety of features of recent glaciation. Marginal moraines, outwash plains, and lake basins predominate, and although present, till plains are less extensive than in the sections to the south.

St. Joseph County has been described by Klear and Stallman (1948) as an area of relatively flat plains crossed by low glacial ridges (Fig. 2). The Maxinkuckee moraine, the largest of these

FIGURE 2.

ridges, begins in the southern part of South Bend and extends southward into Fulton County. The ridge is about 3 miles wide near its northern end and rises about 120 feet above the valley of the St. Joseph River.

Two smaller ridges of the Kalamazoo moraine system extend southward from Michigan into St. Joseph County. One, east of the St. Joseph River, terminates northeast of the campus of the University of Notre Dame. Another narrow ridge, west of the river, extends southward west of South Bend. The main moraine of the Valparaiso system cuts across the northwest corner of the county. These morainal ridges are considerably smaller than the Maxinkuskee moraine in the southern part of the county.

The remainder of the county is comparatively flat, consisting of outwash plain and the alluvial valley of the St. Joseph River, the sand plains adjacent to the Kankakee River, and the upland till plain areas in the south-central and southeastern parts of the county.

Within the limits of South Bend and Mishawaka the local relief is generally small. The valley of the St. Joseph River is about 70 feet below the crests of the hills to the north and seldom over 100 feet below the hills in the southern part of the cities.

The St. Joseph River is the main drainage feature of the area, entering the county east of Mishawaka, running westward through Mishawaka to South Bend where it swings northward into Michigan. The flow of the St. Joseph River is controlled by dams throughout

much of its length. The Kankakee River serves mainly as a drainage ditch in this part of the county flowing to the southwest. Much of the drainage is internal, through the permeable outwash and alluvial material.

Geology

Bedrock is not exposed in St. Joseph County, being everywhere covered by glacial drift. The oldest known formations (Rosenshien & Hunn, 1962) are Ordovician dolomite, dolomitic limestone and shale. The Ordovician rocks are overlain by a sequence of Silurian and Middle Devonian dolomitic limestone, shale, and dolomites, above which is a blue-black, bituminous shale of Devonian age (Logan, 1932) or Devonian and Mississippian age (Patten, 1956). This formation grades upward into shale of Mississippian age, overlain locally by a thin limestone of the same age. Bedrock is not used as a source of water in the area.

Unconsolidated glacial drift of Pleistocene age overlies bedrock. This material ranges in thickness from less than 50 feet to nearly 300 feet. It consists chiefly of glacial Fluvial sand and gravel, clayey till, and some glaciolacustrine clay and silt. The glacial drift is overlain locally by a thin mantle of alluvium, eolian sand, and organically rich sand, silt, and clay of Recent age.

The principal sources of ground water in St. Joseph County are the unconsolidated rocks which form a single but complex

hydrologic system. The glacial deposits are heterogeneous and differ widely in character within a short distance, both horizontally and vertically. Correlation from well to well is difficult, but Klaer and Stallman (1948) classified the drift material into several general categories, differentiation of which is important in a study of ground water resources. These categories are the upland morainal and till plains, the outwash plains and terraces, and the alluvial deposits. The surface extent of these areas is shown in Figure 2.

The upland morainal and till plain materials are predominantly clay or clay with minor amounts of sand, gravel, and rock fragments. These deposits are generally non-water bearing although limited supplies have been obtained from discontinuous lenses of sands and gravels.

The outwash plains and terraces adjacent to the moraines and along the valleys are underlain largely by sand and gravel. These deposits are often cross-bedded and contain interfingering channel deposits of sand and gravel and interbedded, lenticular beds of clay. The clay deposits are believed to separate outwash materials of different ages. Klaer and Stallman (1948) suggested that the deeper sands and gravels were deposited during an earlier substage of Wisconsin glaciation than the shallow outwash, or perhaps even during the Illinois Stage of glaciation. The clay beds may represent either glacial till deposits or lacustrine deposits laid down when the St. Joseph River was dammed temporarily

by glacial deposits.

The alluvial formations along the valley of the St. Joseph River and along the abandoned channels of glacial streams are sand and gravel deposits, generally somewhat more uniform and finer in texture than those of the main outwash plain into which the valleys are cut. Relatively thin strata of clay are interbedded with the sands and gravels. Some of the beds of clay are continuous over extensive areas, others are discontinuous lenses. The clay, although it may comprise only a small part of the total thickness of the alluvial deposits, may be extremely important in confining the water in the underlying water-bearing beds under pressure, and may hinder the recharge of water to these formations.

Within the limits of South Bend and Mishawaka fairly detailed information on the succession of glacial deposits has been compiled from welllogs. The information obtained from these logs is shown by several geologic-sections in Appendix A, Figure A1. The locations of the sections are shown in Figure 3.

In general, the subsurface may be separated into three zones that are usually, but not always present in this area. A shallow zone of water-bearing sand and gravel is underlain by a zone in which clay and glacial till predominate. The clay zone is underlain in turn by a deeper zone of water-bearing sand and gravel. The clay layer separating the shallow gravels from the deeper ones does not present a complete barrier to ground water flow. It is reported to be breached in many places permitting leakage of

FIGURE 3.

water and sufficiently sandy to be slightly permeable. Overall, however, the clay apparently is adequately impermeable and extensive enough to act as a confining layer for the water in the deeper formation, producing artesian conditions.

A profile across the northeast edge of the study area, (A-B) illustrates the relationships existing among the three zones of subsurface material. The principal water-bearing beds lie immediately above bedrock and range in thickness from about 25 feet to nearly 100 feet. These are overlain by a strata of clay and sandy clay which appear to be continuous over a considerable area. The clay becomes thinner near the river where it overlies the sand. The shallow sands and gravel overlie the clay, becoming thicker under the uplands away from the river.

Section C-D shows that the deeper sands and gravels are missing or discontinuous near the central part of the study area, a feature also suggested by section E-F. The channel of the St. Joseph river is cut into the shallow sands and gravels in this area and conditions for natural recharge are favorable.

History of Previous Hydrogeological Investigations

In 1948, the Indiana Department of Conservation, Division of Water Resources published a comprehensive study of the ground-water resources of the South Bend area in cooperation with the U. S. Geological Survey (Klear & Stallman, 1948). The purpose of this report was to determine the safe yield of the aquifers. This investigation was accomplished through a study of the records of existing wells, and of the hydrologic characteristics and extent and thickness of the water-bearing formations. Also included was an investigation of discharge and recharge rates and fluctuations in the ground water level. To accomplish this, a series of observation wells were established throughout the South Bend-Mishawaka area. As the principal aquifers were known to be unconsolidated drift, a study of potential bedrock aquifers was not included.

A contour map of the piezometric surface included in this report is shown in Figure 4. This map is based on reported and measured depths to water in wells for 1945. The water levels were selected to show static conditions unaffected by local pumping. The contours indicate lines of equal elevation of the water in the wells or hydrostatic pressure. From this map the shape of the ground water surface, the direction of flow and the hydraulic gradient may be determined. No attempt was made to separate wells producing from above or below the clay barrier.

FIGURE 4.

Generally, the contour lines of the piezometric surface follow the trough of the St. Joseph River, with the principal exception of the deviation on the west side of the city. This and several other less influential lows were explained as cones of depression produced as a result of heavy localized pumping.

The piezometric surface in the area east and north of the St. Joseph River slopes southwestward toward the river and the ground water would flow in this direction under a hydraulic gradient of from 16 to 55 feet per mile. South of the river, the ground water was reported to flow northward toward the river and the heavily pumped areas from the higher uplands under a hydraulic gradient averaging about 22 feet per mile. West of South Bend the water flowed eastward into the industrial well fields.

The water level in the St. Joseph River was held constant at 680 feet above sea level by the South Bend Dam. The intersection of the contours of the piezometric surface and the river, point P, suggested that ground water was escaping into the river by natural discharge east of this point where the river level was held below the piezometric surface. From that point northward, as far as the dam, the piezometric surface was below the river level and it was considered likely that recharge from the river to the aquifer was taking place.

Below the South Bend dam, the water level in the St. Joseph River was held at 668 feet above sea level and the ground water level appeared to be higher than the level of the river. Here

natural discharge again was assumed to be taking place.

Klear and Stallman concluded that a study of the piezometric surface indicated ground water flows generally toward the river and areas of high pumping rates with hydraulic gradients of between 16 and 55 feet per mile. It was their impression that the effect of the confining clay layer could be estimated only, as it was breached and permeable enough to permit some flow of water through it.

Procedure

Data Accumulation

Records of 18 observation wells located primarily within the corporate limits of South Bend and Mishawaka were selected for this study. These wells were established by the Indiana Department of Conservation prior to and during the investigation of ground water conditions in this area. Generally, the water level observations were made at weekly or bimonthly increments. Records of the wells had been maintained on an intermittent basis and the years of 1945 and 1946 were selected for this study because of the maximum number of wells, 18, in operation at this time. The locations of the observation wells used in this study are shown in Figure 3.

Procedure of Investigation

June 1945 was selected as a trial month in an attempt to determine the most feasible and efficient method of approach. A monthly increment of analysis was considered satisfactory to delineate any fluctuations or adjustments of the ground water regimen. As an initial attempt, data from all wells, regardless of hydrogeologic characteristics, were included to determine the trend surfaces.

The coordinates of each observation well were established with respect to an arbitrary grid system and to each point was assigned the water level elevation, feet above mean sea level, for June 1945. Because the number of possible point locations that could be obtained from the river would exert unproportional influence on the resulting surfaces, the river was not considered as a data point. First-, second-, and third-order statistical surfaces were fitted, by the method of least squares, to the data of the observation wells (Figures 5, 6, 7).

The first- and second-order surfaces appeared to be representative of the piezometric surface map prepared by the Indiana Geological Survey (Figure 4), yet not influenced by individual wells to the extent that the computed surface duplicated the piezometric surface. The third-order surface was found to be too complicated and too greatly influenced by individual well data for trend analysis of the regional piezometric surface.

FIGURE 5

FIGURE 6

FIGURE 7

First- and second-order surfaces for January through December were then prepared. The individual surfaces exhibited variation in gradient and azimuth and the values for the linear surface were plotted on a monthly basis (Figure 8). No trends in the surface elevations, orientations, or configurations were apparent, although it was felt there should have been an indication of seasonal fluctuations in recharge and discharge. This led to a reevaluation of the aquifer conditions.

The data were then divided into two groups on the basis of the hydrogeologic characteristics of the wells. Those wells known to be artesian or to derive their water principally from the lower aquifer were placed in one group, and the water table wells and wells located south of the zone where the confining layer pinches out were placed in the second. The assignment was made on the basis of the report by the Indiana Geological Survey and, where the assignment was indefinite, it was made on the basis of the well logs provided in that report.

The first- and second-order statistical surfaces were determined for each hydrogeologic condition. The division of the data into two sections, however, reduced the number of points available for analysis and for the months of January, February, and March there were insufficient data to provide statistically satisfactory surfaces by the least squares method. To circumvent this, the period of study was changed from calendar year 1945 to the 12 month period from 1 April 1945 to 1 April 1946. The division

FIGURE 8. GRADIENT AND AZIMUTH OF LINEAR SURFACES.

of the data, however, did provide surfaces more responsive to expected fluctuations than the surfaces compiled from the combined data, and the investigations were carried out on the basis of these two populations of wells.

Linear and quadratic trend-surfaces for each month were computed for both aquifers, representative examples of the Cal-comp plots of the quadratic surface are presented in Appendix B. The gradients and azimuths of the linear surfaces were determined and plotted on a monthly basis.

The residuals from each trend surface were examined next. The residuals from the quadratic were considered to be more representative of deviations from the regional trend than the linear residuals as the quadratic surface was a closer approximation to the actual surface than the linear. The mean and standard deviation of the residuals of each well over the 12 month period were plotted for both aquifers at the well locations on the arbitrary grid, although no meaningful contours could be drawn from the data. The mean and standard deviation of the absolute value of the residuals for all wells during each month were also computed and plotted.

The effects of seasonal variation in recharge and discharge were established and then compared with monthly variation in the attitude of the trend-surfaces and fluctuations of the residuals. The actual precipitation for each month of the previous 35 years from 3 locations in the South Bend area was obtained from U. S.

Weather Bureau records. The average of this information was plotted such that the precipitation value for the preceeding month could be compared with test data. For example, the May precipitation would be compared with the June trend-surface configuration.

Likewise, the record of municipal pumping was plotted such that the preceeding month's municipal requirements could be compared with the test data. The water withdrawn from the municipal well fields represented only about half of the total amount withdrawn during the study period. Records of private and industrial requirements were incomplete, however, and it was felt that the records of the South Bend Water Company would be representative of total withdrawal as relative rates of withdrawal are as important in this study as actual amounts.

Results

The separation of the water level data according to the hydrologic characteristics of the wells provided information from which two sets of trend surfaces could be prepared. One set reflected the water table conditions, the other the artesian or semi-artesian environment.

Trend Surfaces

The computed surfaces (Appendix B) exhibited distinct differences in the attitude and configuration under the separated aquifer conditions. The artesian quadratic trend-surface had a closed,

rounded form with a northwest to southeast orientation, the corresponding water-table surface was more acute, with an east-west orientation. The linear surfaces were characterized by dip reversal between the two aquifers although both surfaces had an east-west orientation. The water-table trend-surface dipped to the south, that of the artesian toward the north.

The gradients and azimuths of the linear surfaces were quite different for each aquifer. The gradients of the linear surface compiled from the water-table wells could be divided into two groups (Figure 9), one centered at about 11 feet per mile and the other at 15 feet per mile. The azimuths had a similar relationship (Figure 10A), varying from around 175° to 185° . These values, when plotted against the gradients of each surface, corresponded with the low and high gradients (Figure 11A).

The ranges of gradient and azimuth of the artesian linear surface were much less distinctive. The amount of change was very little compared with that of the linear surface, 1 foot vs 5 feet gradient variation (Figure 9), and 5° vs 16° for maximum change of azimuth (Figure 10B). Contrary to the nature of the water-table surface, little relationship existed between direction of azimuth and gradient (Figure 11B).

The plots of surface orientation revealed that the water-table gradients were depressed during the summer and fall and high the remainder of the year. There were only minor changes in the artesian surface that could be compared with this.

FIGURE 9. GRADIENT OF LINEAR SURFACE.

FIGURE 10. AZIMUTH OF LINEAR SURFACE.

FIGURE II. GRADIENT vs. AZIMUTH, LINEAR SURFACE.

Likewise, the azimuths of the water-table surface were east of south during the summer and fall, corresponding with the periods of low gradient, and west of south when the gradients were at the higher levels. The artesian azimuths fluctuated so little that seasonal variation was not apparent.

Orthogonal Flow Lines

Because of the restrictions imposed by the two aquifer populations and the resulting limited number of control points, the trend surfaces could not be considered satisfactory for the computation of orthogonal flow lines in this phase of the project.

Residuals from Trend Surfaces

The residuals from the computed surfaces were generally smaller for the quadratic surfaces than for the linear surfaces; this was attributed to the quadratic surface being more representative of the actual surface than the linear. Residuals from the quadratic surfaces were used for this reason.

When the means of the residuals from the quadratic surface were plotted at the respective well locations (Figure 12), their distribution, magnitude and algebraic sign, were such that there was no apparent segregation of values in any particular area. This was the case for both the water-table and artesian aquifers. Likewise, standard deviations of the absolute value of the residuals of each well over the study period were plotted with no apparent differentiation of values for either formation (Figure 13).

FIGURE 12

FIGURE 13

The mean absolute value of the residuals and the mean standard deviation of the residuals for all the wells in each aquifer were determined for every month of the study period and plotted on a monthly basis. As shown in Figure 14, note the range of the fluctuation of the mean absolute value of the residuals from the artesian surface was less than that of the water-table surface. This was also the case for the mean standard deviation of the residuals (Figure 15). The variation of the standard deviation from month to month indicated a significant difference in the two aquifers. For the water-table aquifer there was a grouping of values at approximately 5 feet and one at 15 feet, the higher values occurring generally during the summer months. For the artesian aquifer, the mean standard deviation of all wells remaining generally constant throughout the year.

Recharge and Discharge

The nature and amount of discharge from the aquifers for each month of the study period is presented in Figure 16, showing an expected heavy demand during the summer months. The average precipitation recorded at three stations in South Bend is plotted in Figure 17, showing considerable variation in monthly increments.

Analysis

The results of this investigation presented in the preceeding section illustrate several important features of the hydrogeologic environment in the South Bend-Mishawaka region. Foremost among

FIGURE 14. MEAN OF ABSOLUTE VALUE OF RESIDUALS.

FIGURE 15 STANDARD DEVIATION OF RESIDUALS FROM QUADRATIC SURFACE.

FIGURE 16. DISCHARGE FROM CITY OF SOUTH BEND WELL FIELDS.

FIGURE 17. PRECIPITATION; MONTHLY AVERAGE OF THREE RECORDING STATIONS IN SOUTH BEND.

these is the independent nature of the two aquifer systems. Secondly, there is the response of both aquifers, as represented by trend-surfaces, to seasonal changes in recharge and discharge. It is also noteworthy to consider the lack of apparent relationships existing among the residuals from the trend-surfaces that could be explained as a result of localized geologic or hydrologic influence.

The independent nature of the two aquifers is apparent when the fluctuations in gradient and azimuth of the linear surfaces and the means and standard deviations of the residuals from the quadratic surfaces for the separate aquifers are compared. This is illustrated by the reversal of the dips of the linear surfaces mentioned previously. This reversal possibly is the result of the hydrologic characteristics of the area, indicating different areas of recharge and discharge and possibly the effect of the St. Joseph River. Additional data would have to be analyzed to determine the exact cause of this anomaly, however, the importance of the dip reversal is that it indicates that the two aquifers were influenced by different factors.

The close relationship between azimuth and gradient of the linear surfaces, particularly the water table, suggested that the surfaces had a definite orientation and configuration, subject to particular variations in the ground water regimen. The movement of the contour lines on the computed surfaces represented the response fluctuations of the trend-surfaces to raising or lowering

water levels.

The comparison of the data with time is revealing and may be used to illustrate significant points about the ground water regimen. The response of each aquifer to seasonal changes in discharge and recharge emphasizes their independent nature and also, more importantly, the sensitivity of the trend-surfaces to fluctuations in recharge or discharge. An inverse relationship exists between the gradient of the linear surface of the water-table aquifer (Figure 9) and precipitation (Figure 17) during the summer months, indicating rapid response to surface precipitation and recharge. The corresponding artesian gradients reflect predictably less sensitivity to variation in precipitation. As mentioned previously, gradient and azimuth of the linear trend surfaces are closely related, and a comparison of precipitation with azimuth yields the same results.

The general agreement between fluctuation of the artesian surface and fluctuation in precipitation is not unexpected. However, the inverse relationship between fluctuation of the water-table surface and precipitation requires further investigation.

The relationship between discharge (Figure 16) and precipitation generally correspond with the periods of large pumping requirements. When the change in water-table gradients (Figure 9) is related to discharge, it becomes apparent that there is an inverse relationship between them. Thus, even

though precipitation and discharge reach peak amounts during the same period, the influence of discharge on the water-table surface is great enough to overshadow the effect of increased recharge.

The period of high gradients of the artesian aquifer corresponds directly with the high periods of both recharge and discharge during the summer months. Comparing this relationship with that of the water-table aquifer indicates that the artesian aquifer is less influenced by high pumping rates than the water-table aquifer.

The fluctuations of the aquifers, as disclosed by the standard deviations of the wells also exhibit an independent response to seasonal change. A comparison of the changes of the standard deviations of the water levels in the water-table aquifer (Figure 15) with varying amounts of precipitation indicates that peak fluctuations occur during periods of maximum precipitation. This same relationship exists between the standard deviations and rates of discharge, suggesting that this aquifer responds very rapidly to changing conditions of recharge and discharge. Fluctuations in the artesian aquifer are minimal, showing little response to varying recharge and discharge. This aquifer appears to maintain a more steady state throughout the year.

As noted previously, the municipal wells from which the discharge data were obtained, pump mainly from the artesian aquifer.

The steady state characteristics of this aquifer as indicated by the study of the standard deviations of the water level fluctuations can only be explained by relative large coefficients of transmissibility and storage capacity such that the withdrawn water is readily replaced. Otherwise, the artesian system would be expected to show more sensitivity to variations in the pumping of the wells. The sensitivity of the water-table aquifer to pumping in the municipal wells can be explained by the close relationship that exists between the requirements and peak periods of the industrial and private wells, tapping the water-table, with those of the municipal wells, pumping from the artesian aquifer.

The absence of any grouping or organization of the residuals, or mean value of the residuals, from the quadratic surface of both aquifers (Figure 12) must be carefully considered. It suggests that location alone is not a controlling factor in determining the water levels of the area, hence the effect of geologic changes in the subsurface and areas of concentrated pumping or recharge would appear to be of minor importance toward influencing rates and directions of ground-water flow in the South Bend area. Evidence indicates that the transmissibilities of the aquifers are great enough that minor changes would not be important. The lack of any definite pattern or congregation of the residuals, either plus or minus values, precluded the location or identification of areas where current discharge was exceeding

recharge, and also, of areas where potential ground water resources appeared to be most favorable for future development. There are, however, a limited number of wells monitoring each aquifer, and the possibility exists that some areas of essentially positive or negative residuals were not strong enough to be delineated with the open spacing.

The likelihood that changes in the subsurface have little influence on the groundwater regimen is reinforced by examining the plot of changes in the standard deviations of water level fluctuations in each well (Figure 13). Here, as when the residual values themselves were examined, there is no evidence of grouping or segregation of high or low values. Important here also, is the fact that standard deviations at the wells of both aquifers show no relationship whatsoever with the river. It would be expected that those wells near the river would be subject to greater changes in water levels, hence greater standard deviations. However, it is possible that with the very high permeability values reported for the aquifers and with the river being maintained at a constant level, fluctuations in the water levels are not appreciably different over the study area. It must be considered, also, that the true effect of the river is masked by other features, such as variable pumping at different locations, and as such, cannot be determined from this type of investigation.

This analysis of the hydrogeology of the South Bend-Mishawaka

area and of aquifer characteristics leads to conclusions that generally agree with those presented by Klear and Stallman (1948) and Rosenshein and Hunn (1962). This is particularly true with respect to the high values of transmissibility and of the influence of seasonal variations of recharge and discharge on general water levels. The period over which this investigation was carried out, however, was insufficient to allow any reliable comparison with their analysis of the long-term ground water conditions.

The conclusions developed from the study of the fluctuations and residuals of the trend surfaces representing water levels of the two aquifers, however, indicate that the independent nature of the separate systems is more pronounced than had been believed. There is evidence also that the influence of the St. Joseph River on the ground water regimen may be less than anticipated.

BARTHOLOMEW COUNTY INVESTIGATION

Description of Area

Bartholomew County is located in south-central Indiana, (Figure 1). The city of Columbus, the county seat, is in the center of the county, approximately 40 miles southeast of Indianapolis and 70 miles north of Louisville, Kentucky. The population of Columbus was 20,778 in 1960, according to U. S. Census Bureau figures, comprising approximately one-half of the total population of Bartholomew County. The area is essentially an agricultural region, with the exception of the industrialization center at Columbus and the military facilities at Camp Atterbury and Bakalar Air Force Base.

The climate is typical of southern Indiana with an average annual precipitation of about 40 inches well distributed throughout the year. With the exception of a few small streams flowing west into Salt Creek, all of the county drains into the East Fork White River, flowing southward from its formation at the junction of Driftwood River and Flatrock Creek near Columbus, Figure 18.

Physiography

Bartholomew County consists of a series of flat to rolling glaciated plains terminating on the western edge in a rolling upland that rises more than 200 feet above the adjoining plains. The undulating, slightly morainic Wisconsin glacial till plain in the eastern part of the county is separated from the flat, stream-dissected Illinoian till plain on the west by the alluvial valley of the East Fork White River. Parts of three physiographic

regions (Mallot, 1922), the Norman Upland, the Scottsburg Lowland and the Muscatatuck Regional Slope occur in the county, Figure 18.

The Normal Upland includes the western part of Bartholomew County. It is characterized by rugged hills and narrow, steep-sided valleys formed in the resistant Borden Group of shales and sandstones of Mississippian age. The eastern boundary of the Norman Upland is an escarpment known as the Knobstone Escarpment, where the elevation drops several hundred feet to the level of the Scottsburg Lowland.

The Scottsburg Lowland occupies the central portion of the county. It is a low plain extending from the base of the Knobstone Escarpment eastward to the boundary with the Muscatatuck Regional Slope which is obscured by glacial drift. The boundary runs north and south, roughly paralleling the line between ranges 6 and 7 east of Flatrock Creek and East Fork White River. Its designation "lowland" is due to the pre-glacial erosion of the relatively less resistant Devonian-Mississippian New Albany shale and the overlying lower shales of the Borden Series.

The Muscatatuck Regional Slope is formed of resistant limestones of Devonian and Silurian age which slope upward at about 15 feet per mile in a northeasterly direction. It is a moderately dissected, undulating plain with entrenched stream valleys cutting 20 to 50 feet into the glacial till and underlying limestone.

The bedrock topography, as shown in Figure 19, was determined from well records and seismic data. The predominate feature is a north-south trending drainage system established prior to the advance of continental glaciation. Geologic sections were drawn across the principal valley, Appendix A, to illustrate the thickness of glacial fill above the bedrock surface. The location of these sections is shown in Figure 20. The valley corresponds with the Scottsburg Lowland physiographic region.

Geology

Glaciation by both Illinoian and Wisconsin ice-sheets greatly modified the topographic features of Bartholomew County. The Scottsburg Lowland and the Muscatatuck Regional Slope were covered by parts of three different advances of glacial ice.

The southern limit of Illinoian glaciation passes southward through central Brown County 15 miles west of Columbus and through the western part of Jackson County, continuing in a southeasterly direction to the Ohio River. The major part of Bartholomew County is covered by a thin mantle of Illinoian glacial till or boulder clay, generally less than 25 feet thick. The main part of this ice-sheet did not extend westward beyond the Knobstone Escarpment, although along the margin there is a thin belt of glacial deposits on the sandstone and shale bedrock.

After the retreat of the ice front the area was exposed to weathering and erosion for a considerable length of time as

BARTHOLOMEW COUNTY INDIANA
BEDROCK CONTOUR MAP

Redrawn from a Preliminary Map Prepared by the U.S. Geological Survey
Contour Interval 20 feet. Datum msl

FIGURE 19.

FIGURE 20.

remnants of a buried soil zone in the eastern half of the county have been reported by Malott (1922).

Early Wisconsin ice covered the northern and eastern areas of the county, advancing as far south as Columbus, Figure 18, and depositing a layer of drift ranging in thickness from 10 to 50 feet. Late Wisconsin glaciation entered the northern part of the county and deposited isolated tongues of glacial till marked in some places by a terminal moraine 10 to 20 feet high. The extent of Wisconsin drift is interrupted in the central part of the county by a large gravel-filled valley that served as a sluiceway for water from the melting Wisconsin ice fronts, Figure 20.

These outwash deposits have been terraced as a result of varying conditions of erosion and deposition, the terraces being particularly well developed north of Columbus. South of Columbus along the eastern side of the East Fork White River Valley and on the upland beyond, are scattered areas of old sand hills.

The valley is currently occupied by a composite of several present-day streams, principally Flatrock Creek, Haw Creek, Clifty Creek, and to a certain extent, Driftwood River, all of which join to form East Fork White River south of Columbus. The outwash materials filling this valley are capable of absorbing and storing large quantities of ground water, thereby creating a vast underground reservoir. It is part of this reservoir that was selected for study in this investigation.

The sand and gravel deposits of the outwash valley are the major aquifers in this area. Most of the bedrock wells obtain little or no water from the New Albany shale and are drilled to the underlying Devonian limestone only when no other supplies are available.

In the northern part of the study area, one branch of the outwash-filled valley lies east of the Driftwood River, extending in a southeasterly direction to join a similar branch of the valley along Flatrock Creek. At this junction it is nearly nine miles wide. The valley continues in a southeast direction passing east of Taylorsville southward through Columbus. South of Columbus it is joined by the smaller valleys along Haw Creek and Clifty Creek. In this area it is about three miles wide.

Associated with the main valley, but of much lesser extent is the valley presently occupied by the Driftwood River from Taylorsville south to Columbus. This is a very narrow valley, filled with shallow outwash deposits. The west side is formed by the Illinoian glacial material, the east side by an island ridge approximately $5\frac{1}{2}$ miles long and a half a mile wide, probably of Wisconsin age till.

Records of existing wells indicate that the outwash deposits are essentially sand and gravel, reaching a maximum thickness of over 100 feet. The composition varies considerably in character in both the horizontal and vertical directions, and some clay layers of limited extent are reported in drillers logs.

The limits of the lateral extent of outwash deposits are difficult to define precisely because of the gradation associated with glacial drift. In addition, the eastern boundary is obscured by the valley of Clifty Creek and Haw Creek although the limit of till apparently extends to the east lines of Sections 17, 20, and 29 of T9N, R6E. West of this boundary, little clay has been reported as far as the area underlying the western part of Columbus. Here, the glacial deposits are relatively thin and are composed mainly of clay, yielding little water to penetrating wells. West of Columbus, the glacial materials increase in thickness until the western limit, generally considered to be along a line running from Taylorsville to the Columbus airport (well #1), is reached. The shallow valley of the Driftwood River, however, may be considered to be an extension of the system.

Klaer, Davis, and Kingsbury (1951) reported that the width of the permeable sands and gravels becomes reduced from about 5 miles near Taylorsville to about 2 miles in the vicinity of Columbus, and that the thickness and permeability of the materials remains essentially the same throughout the area.

History of Previous Hydrogeological Investigations

In 1951, the Indiana Department of Conservation, Division of Water Resources, published a report on the ground water resources of the Columbus area in cooperation with the U. S.

Geological Survey (Klaer, Davis, and Kingsbury, 1951). The purposes of this report was to determine the safe yield of the water-bearing formations available for the expected demands of Columbus. This investigation was accomplished through a study of existing wells, by evaluating the thickness, extent, and hydrologic parameters of the aquifers and by investigating the recharge and discharge rates and fluctuations of ground water levels. In addition, a pumping test was run on a newly-drilled well in the Columbus well field to provide specific quantitative information on the aquifer. As the main water-bearing formation was known to be the unconsolidated deposits of sand and gravel, no attempt was made to evaluate the potential of the bedrock formations.

An investigation of -between surface-stream flow characteristics was included in this report in an attempt to classify the disposition of the average rainfall and the relationship existing between the surface water and the ground water system. Stream flow measurements were made to define influent and effluent reaches of Driftwood River and the results extended to Flatrock and Haw Creeks.

The amount of water draining into the streams during dry periods, i.e. base flow, was determined to be about equal to the average annual recharge to the ground water reservoir in the upper regions of the valley. Study of the subsurface geology and bedrock topography revealed, however, that the width of the

permeable sands and gravels becomes greatly reduced north of Columbus.

If conditions of permeability, thickness, and hydraulic gradient remained essentially the same, which records of well logs and water levels indicated to be true, the ground water moving southward should enter the surface streams in this area.

The validity of this assessment of ground water-surface water relationships was checked by Furness and Buxton (Klaer, Davis and Kingsbury, 1951) by making several stream measurements on Flatrock and Haw Creek. Their findings essentially reinforced this hypothesis, indicating that between points B and C on Flatrock Creek and E and F on Haw Creek (Figure 20) part of the water flowing underground north of these zones drains from the ground into the streams and passes southward as surface-stream flow. This is essentially where the width of the section through which the underflow must pass is greatly decreased.

The conclusions reached about the ground water regimen from this investigation may be summarized as follows:

1. The coefficient of storage for the sand and gravel formations is 0.12.
2. The transmissibility of these formations may be taken as 300,000 gal/day/ft.
3. There is evidence of a hydraulic connection between Flatrock River and Haw Creek and the ground water reservoir. Although the pumping test did not verify this,

the presence of a shallow clay seal in Haw Creek near the well field was considered to have influenced these results.

In 1964, SIECO, Inc., consulting architects and engineers, designed and supervised construction of replacements for four of the six wells in the Columbus well field. As part of this work, a re-evaluation of the ground water reservoir both north and south of Columbus was conducted and a test pumping program was carried out for two of the new wells. Additional stream flow measurements were made on Flatrock Creek and East Fork White River to determine any changes that might have occurred in the volume of surface water flow that would influence ground water-surface water relationships.

The results of this study were presented in a 1965 report by SIECO, Inc. for the Columbus Water Utilities Board (SIECO, 1965). The findings essentially reinforce those of the previous study with the exception of the following conclusions:

1. The storage coefficient was re-evaluated to be 10 per cent.
2. Transmissibilities of the two test wells were determined to be 650,000 gal/day/ft and 450,000 gal/day/ft. An average of 550,000 gal/day/ft. was considered best for computations of aquifer parameters.
3. There had been a general lowering of the water table throughout the study area with a corresponding flattening

of the gradient.

4. There was no noticeable change in the relationship between surface water and ground water, although lowering water tables had changed the amounts of water available for stream recharge.

Following the report by SIECO, INC., the U. S. Geological Survey, in cooperation with the Indiana Department of Conservation, Division of Water Resources, initiated the construction of an analog resistor model of the unconsolidated water-bearing formations in the Columbus area as part of a comprehensive water resource evaluation. To implement this investigation, a series of 42 shallow observation wells were established to monitor water levels in the unconfined aquifer. Water-level measurements were taken every six months and conventional contour maps of the ground water surface prepared to show the position and configuration of this surface and to illustrate the changes and fluctuations that were taking place with time. A copy of the April 1965 map is included as Figure 21.

Generally, the water table may be described as sloping toward the south end of the valley at approximately 5 feet per mile, swinging up into the valleys of the tributary streams. There does not appear to be any significant lowering of the surface around Columbus, although the heavy concentration of pumped discharge might be expected to form a local cone of depression. Towards the north end and on both sides of the

valley the boundaries of the aquifer are established by the much less permeable glacial till.

The analog resistor model has not been completed at this time. However, the results of this analog approach when compared with the results of this report, should provide an excellent opportunity to relate the advantages and disadvantages of two newly developed divergent techniques of water resource evaluation.

Procedure

Data Accumulation

Periodic records of 42 observation wells monitoring the water level in the sand and gravel aquifer in central Bartholomew County were available for use in this phase of the investigation. These wells, together with stream level measurement stations were established by the U. S. Geological Survey to provide hydrogeologic information for the analog resistor model study of this aquifer. In addition, the records from 5 continuously recording observation wells located primarily in the Columbus area were available. The location of those wells used for this study are shown in Figure 20.

Records for the continuously recording wells were available from the time of their installation, in some cases many years. It was not considered feasible, however, to attempt to evaluate water level conditions solely from the information provided by the

records of the 5 continuously recording wells. As data from the additional wells were available only at six-month intervals, the trend surfaces were computed accordingly in the spring and fall of each year during periods in which it was hoped that the ground water levels would be at their extremes. Because the maximum amount of data on water level fluctuations was available after April 1965, the two year period from April 1965, to April 1967 was selected for study.

Procedure of Investigation

Following the general procedure worked out during the trend-surface analysis of the ground water regimen at South Bend, the coordinates of each observation well were established with respect to an arbitrary grid system and the water level elevation in feet above mean sea level was assigned to each point. Data from April 1965 were used for a test run.

The stream measurement data recorded by the U. S. Geological Survey were not included in the analysis. Review of the records indicated that the surface flow was subject to short term fluctuations and that much of the flow was derived from portions of the drainage basin outside the boundaries of the study area.

Because of the impermeable ridge of glacial till separating the aquifer occupying the valley of Driftwood River from the main aquifer east of the ridge, Driftwood Valley was considered as an extension or arm of the principal aquifer. Water level data from this valley were included in the study to evaluate the

relationships between the two and to determine the influence of the Driftwood system on the overall hydrologic regimen.

First- and second-order surfaces were fitted to the observational well data for April 1965. The linear surface described the overall gradient and direction of the slope of the ground water table when it was compared with the surface contoured by conventional means by the U. S. Geological Survey. The second-order surface closely approximated the configuration of this surface with respect to both gradient and shape. When the residuals from the second-order surface were examined, however, several features were revealed which appeared to deviate from the expected results and which warranted further detailed examination.

One of these features was the nature of the residual for well number 40 at the north end of the county. The residual from the quadratic surface at this location was more than six times greater than the standard deviation from the mean quadratic residual. An inspection of the log and well site indicated that this well was obtaining its water from a 4-foot thick layer of sand within the glacial till rather than from the body of sand and gravel valley fill. Water level data from this well, therefore were not considered to be representative of the aquifer under study. This example illustrates an advantage of this method of hydrogeologic study, i. e., the recognition of more than one aquifer population

An additional feature revealed by an inspection of the res-

iduals was the fact that the residuals for the wells located at gravel pit sites were all positive. None were negative as would be expected if the basic assumptions about the nature of the residuals were valid. Inspection revealed, however, that most of these locations were at small, shallow, long-abandoned pits in which organic and fine-grained sediments had accumulated. To compound the problem, many of the actual well casings could not be located, having been removed or destroyed. In those that could be located, the water level was often standing above ground level or, in many cases, could not be determined accurately. Uncertainties associated with the water level measurements made in the gravel pit observation wells were considered sufficient to bias their value and they were not included in further trend-surface evaluations.

New first- and second-order surfaces were computed for April 1965, as were surfaces for October 1965, November 1966, and April 1967, (Appendix C). All the foregoing computations were based on the data from 33 wells considered to provide representative information on ground water levels of the aquifer under study. Data for April 1965 for observation wells without recording equipment was not available and no surfaces were prepared for this month. An additional second-order surface was computed for December 1966, and orthogonal flow lines were drawn to the trend-surface contours for the determination of ground water flow directions and relative rates.

The residuals from the quadratic surface, considered to best represent deviations from the actual water level surface were determined, plotted at the respective wells, and contoured.

(Appendix C) In addition, the mean and standard deviation of the mean of the absolute value of the residuals for each well, taken over the study period, was calculated and plotted on a similar basis.

Although insufficient data precluded a month by month trend-surface analysis of the ground water levels being carried out in Bartholomew County, the effects of seasonal variation in discharge and recharge were established for comparison with the spring and fall surfaces. It was hoped that these surfaces would reflect seasonal variation, if not monthly variation, although the sensitivity of the surfaces to such cumulative variation would be reduced.

Results

The quadratic surfaces resulting from the trend-surface analysis of ground water data are presented in Appendix C. These maps were produced by a standard Calcomp plotting routine, and a representative example, April 1965, is shown in Figure 22. The boundaries of the study area, as established by the location of observation wells and the extent of the sand and gravel formations comprising the aquifer, are outlined and have been superimposed on this map. The surfaces slope at a gradient southward at approximately 10 feet/mile. Although the position of individual con-

tour lines varies from period to period, the general slope and configuration of the surfaces remains essentially the same for the duration of investigation. The orthogonal flow lines drawn to the trend surface contours, Figure 23, illustrate the direction and relative amounts of ground water flow.

The maps of residuals from the quadratic surface illustrate distinct areas of positive and negative residuals. They also are presented in Appendix C, and a representative example is shown in Figure 24. As with the quadratic surfaces themselves, the position of individual contour lines varies over the study period, but the general shape and position of the areas of positive and negative residuals they define remain fixed. One of these areas, of negative residuals, is located in the south-central portion of the study area, directly south of Columbus along the lowlands of the East Fork White River. Zones of positive residuals are to be found both to the east and to the west of this negative area. A third region of positive residuals is located north and northeast of Columbus. The maximum values of positive residuals are found in what might be termed a residual high in the eastern part of this area.

The standard deviations of the mean value of each well were also plotted, Figure 25. The areas of maximum deviations appeared in the area northeast of Columbus and in an area to the west of Columbus in the Driftwood Valley. An additional zone of relatively large fluctuations was evident in the Columbus area itself.

FIGURE 22. QUADRATIC SURFACE, APRIL 1965.

FIGURE 23. ORTHOGONAL FLOW LINES, DRAWN TO CONTOURS OF QUADRATIC SURFACE.

FIGURE 24. RESIDUALS FROM QUADRATIC SURFACE, APRIL 1965.

FIGURE 25. STANDARD DEVIATIONS OF RESIDUALS.

Minimum standard deviations were observed for areas southeast and southwest of Columbus.

An additional ground water surface map, in this case one corresponding to the actual ground water in the observation wells for April 1965, was prepared for comparison with the map of the computed quadratic surface and the water level maps drawn by conventional hand contouring. This map is presented in Figure 26. The quadratic surface representation of the actual topography, as determined from the elevation of the observation wells, was also plotted for a comparison with the ground water surface maps, Figure 27. In addition, the residuals from the quadratic topographic map was also plotted, Figure 28.

Analysis

The results of this investigation, presented in the preceeding section reveal much about the geohydrology of the study area. Features such as the configuration of the ground water table, the gradient under which ground water flows, and the effects of local or seasonal fluctuations in discharge and recharge are revealed by the computed surfaces. In addition, anomalous areas of the ground water regimen are defined by the residuals for further study. It is a unique advantage of the Bartholomew County study that the information provided by the statistical evaluation may be verified or explained through a comparison with data from previous conventional hydrogeologic surveys.

FIGURE 26. COMPUTER CONTOURED WATER TABLE SURFACE, APRIL 1965.

FIGURE 27. QUADRATIC SURFACE COMPUTED FROM TOPOGRAPHIC DATA.

FIGURE 28. RESIDUALS FROM TOPOGRAPHIC QUADRATIC SURFACE.

When evaluating the characteristics of the computed surfaces, it is interesting to note the relationship between the conventionally contoured surface, Figure 21, and the computer contoured surface for the same month, April, 1965, Figure 26. The close similarity between the shapes of these two surfaces is immediately apparent. The principal difference between them being the characteristic of the hand contoured surface to swing further up into stream valleys. The fact that the machine contoured surface does not is not so much a characteristic of machine contouring, rather than from the fact that water levels taken from stream measurements were not included in the contouring program. The gradients of both surfaces are nevertheless equal over the extent of area covered.

When these surfaces are compared with the quadratic representation of the water table surface for the same month, Figure 22, it may be seen that the quadratic surface retains the same gradient and overall general configuration. The sensitivity of the fitted quadratic contours to effects of localized water table influence is less pronounced than for those of actual surfaces. This is because the fitted surface reflects regional trends whereas conventionally-drawn contour maps (topographic, isopach, piezometric, etc.) show all variations. The general agreement between the quadratic surface and the actual surface computed from the same data for the same time period, although subjective, illustrates that the quadratic surface may be considered to replicate the actual water table

surface less local anomalies.

The addition of orthogonal flow lines to the contoured second order surface, Figure 23, shows several important features of the ground water regimen. The gross regional flow is from north to south as would be expected. However, it is interesting to note the tendency of the flow lines to swing to the northeast, reflecting the influence of the ground water flowing through the aquifer in the vicinity of Flatrock and Haw Creeks. This tendency suggests that much of the total ground water flow is provided from this area and that relatively little flow is contributed from the valley of Driftwood River. The influence of Clifty Creek along the eastern border could not be established within the limits of the study area.

The effect of topography on the ground water table appears to be influential as would be expected. A quadratic surface was computed for the ground-level elevations at the individual observation wells used in the ground water survey, Figure 27. The attitude and configuration of this surface is almost identical to those of the water-table quadratic surfaces, with the exception that the values of the contour lines are 10 feet to 15 feet higher than the corresponding values of the water surface. The slope is roughly 10 feet/mile for both surfaces, extending from a high in the northeast corner to the southern boundary of the study area.

No observation wells were situated on the "island" of glacial till parallel to and on the east side of Driftwood River. The

influence of this impermeable ridge on the hydrologic regimen therefore was not noted on the computed water level quadratic surface maps, nor was it noted on the computed topographic map as no elevations from the ridge were used in the compilation of this map. The aquifer was considered to be a continuous unit for the computing and plotting of the trend surfaces, the area occupied by the ridge being a blind spot in which no data were available.

The validity of this assumption was tested by evaluating the nature of the computed water table surfaces and the values of the residuals for the wells located in the Driftwood River valley. Had a deflection of the surface been apparent or had the values of residuals been incongruous with corresponding values on the east side of the ridge, this assumption could not be considered to be valid. Examination of the surfaces and the residuals, however, gave no reason to believe that there were any unique conditions of the ground water regimen that would indicate the Driftwood Valley was a separate hydraulic unit. This in effect reinforced the hypothesis that the valley of the Driftwood River acts as a branch or as an extension of the main aquifer, and that ground water levels in this aquifer were subject to the same fluctuations with varying recharge and discharge as those east of the ridge

Review of the maps of the residuals from the quadratic surfaces, suggested that there are essentially four regions in the study area where the larger residuals, positive and negative, are

centered. These areas generally remain in the same position and do not vary in location. It must be noted, however, that the position of the quadratic surfaces themselves do not change to a great extent during the period of investigation. Hence, the stable nature of the residuals cannot be considered to have been tested under extreme conditions.

The four centers of larger valued residuals, however, were assumed to be stable under normal fluctuations of recharge and discharge. It is interesting to note that one area where negative residuals might be expected to be found did not materialize. This is the east side of Columbus, along Haw Creek, where the municipal and industrial pumping is centered. There is no evidence of negative residuals predominating here as might be expected in an area where concentration of discharge could cause a localized lowering of the water levels. The absence of such a feature indicates that the amount of water available for discharge is adequate and that the permeability of the aquifer is large enough so that no significant cone of depression has formed. This illustrates another use of this method, i.e., localization of influence from artificial discharge by use of residuals to a mean surface.

The basis for the particular centers of either positive or negative residuals to be located in certain areas may be explained through a study of the topography, geology, or hydrology of each site. In areas where localized discharge or recharge in the ground water system influences water levels, the residuals likewise are

influenced and may be used to evaluate the effects of recharge or discharge. In areas where topography influences ground water levels, such as across a normal values cross-section, the relationship between positive and negative residuals is that the negative values are to be found in the center of the valley, the positive values, flanking the central area on both sides. This appears to be the explanation for the zone of negative residuals south of Columbus. The negative values are grouped in the area corresponding with the lowlands of the East Fork White River Valley, while east and west of this, over areas considered to be the higher upland regions, zones of positive residuals are found.

This analysis may be verified by comparing a map of residuals from a quadratic water level surface, Figure 24, with the map of residuals from the quadratic topographic surface, Figure 28. South of Columbus, a central area of low or negative residuals along the East Fork White River lowlands is flanked by high positive residuals to the east and west. This correlation emphasises the effect of topography on ground water levels in this area, and since this agreement between topographic and water-surface residuals is not apparent immediately north of Columbus, it indicates that other factors must be considered to explain the existence of the strong area of positive residuals in this area. Therefore, this approach to hydrogeologic data permits the isolation of areas with abnormal water levels.

A study of the map of the bedrock topography, Figure 19, suggests

that the width of the Flatrock River Valley and the width of the permeable sands and gravels within it, becomes reduced from about 5 miles near Taylorsville to about 2 miles in the vicinity of Columbus, while the thickness of the aquifer remains about the same. Assuming this to be the case, the quantity of ground water that flows through the 5-mile width of the valley must be considerably greater than that which could pass through the 2-mile width.

Records of well logs and water levels indicate that the permeability, thickness, and hydraulic gradients remain about the same in this area. The volume of water that is moving southward as ground water thus cannot all continue as underflow, hence it must enter the surface streams in this area where the aquifer is constricted. At the same time it could be expected that the aquifer would remain fully saturated in this area, being adequately permeable to replace water withdrawn from the formation and less subject to fluctuations in recharge and discharge than other areas of the aquifers as only the excess water will be yielded to the surface streams.

L. W. Furness and E. R. Buxton of the U.S. Geological Survey (Klaer, Davis, and Kingsbury, 1951) made several measurements of stream flow in Flatrock Creek and Haw Creek to check the relationship between surface streams and the ground water regimen in this area. The location of the stream discharge measurements made in this study is indicated on Figure 20.

The discharge in second feet per square mile was computed for

several sections of the drainage basins as a basis for comparison. In the Flatrock basin, the additional discharge per square mile picked up by the stream between points B and C was considerably greater than the average for the basin, indicating that part of the water flowing underground in the northern part of the basin was draining from the ground into the stream and passing southward as surface flow.

The decrease in runoff per square mile between points D and E in the Haw Creek valley indicated that water was being lost to the ground water reservoir. As in the lower part of the Flatrock basin, however, the runoff per square mile between points E and F in the Haw Creek basin was also considerably above the average for the basin, indicating drainage from the ground water reservoir to the stream.

Both of the areas where ground water was found to be flowing to surface streams were in the area where the width of the valleys of Flatrock Creek and Haw Creek, and the width of the section through which the ground water must pass is greatly decreased. This area also corresponds with the zone of positive residuals north of Columbus where, as mentioned previously, negative residuals would normally be expected to be found. This relationship suggest that the positive residuals were the result of valley constriction and the associated over-saturation of the aquifer. The area delineated by the positive residuals is in this case an area where water levels remain above average as a result of natural features affecting the

hydrogeologic regimen. This area would seem to be particularly favorable for future ground water development, a conclusion made possible by this method of study.

The reason for the very high positive residual found consistently at observation well 26 northeast of Columbus is unclear. No geologic or hydrologic explanation for the anomaly could be found although the topographic and geologic environments were extensively reviewed. Consultation with Mr. Frank Watkins, U S Geological Survey, revealed that this well was proving to be anomalous in the analog study also, and that it was being investigated in detail in an attempt to explain the basis for its action.

A study of the contoured map of standard deviations, Figure 25, indicated several areas of large fluctuations. All of these areas, one in Driftwood Valley, one northeast of Columbus along Flatrock Creek, and the other along the west side of Columbus, were areas found to be shallow sand and gravel deposits. This feature suggests that the storage capacity of the aquifer in these areas was such that changes in discharge demands or recharge immediately influenced ground water levels, leading to the conclusion that they would be unsatisfactory for development of ground water resources.

Verification of Trend-Surface Analysis

The principal objective of this investigation, as defined by the statement of the research problem, was to develop a better understanding of the relationships existing between

geologic conditions and the hydrogeologic regimen through the application of trend-surface analysis. It was hoped that one of the results of this investigation would be the facility to establish areas which could or could not support greater ground water withdrawal. Such areas, delineated by the positive residuals from the trend-surface maps and found to be based on favorable hydrologic factors, would then be studied in detail for potential ground water development.

In the Bartholomew County study, the area of positive residuals north of the city of Columbus had been found to be the result of unique conditions of the subsurface geology and ground water flow. This area was considered to be a favorable area for the development of future ground water resources and a field testing program was initiated to evaluate the aquifer parameters. The results of this test were to be related with those of previous tests of the same aquifer to determine the relative potential of the ground water resources in the area chosen from the trend surface analysis compared with overall aquifer characteristics.

A site was chosen at Bakalar Air Force Base, Figure 20, approximately in the center of the area of positive residuals. Budget considerations limited the extent of testing and a 24-hour pumping test from an 8-inch diameter well was the maximum that could be carried out. The test well was drilled to bed-rock as was 1½-inch observation well 100 feet south of this well.

In addition BA-6, a continuously recording observation well established by the U. S. Geological Survey, located 200 feet south of the pumping well, served as a second observation well. The observation well was logged with gamma-ray logging equipment to evaluate subsurface conditions at the test site. The log is included with the drillers logs of both the observation well and the pumping well in Appendix D. These logs show approximately 80 feet of coarse sand and gravel above the bedrock surface.

A standard 24-hour pumping test was started in which 275 gallons per minute were withdrawn from the well. It became apparent that this was not great enough to thoroughly test the aquifer and the rate was increased to the maximum possible for the pump system installed in the well, 320 gallons per minute. This also, however, was insufficient to completely test the aquifer.

The values determined for the coefficients of transmissibility and storage were nevertheless approximated from a distance-drawdown curve. The resulting calculations indicated that the coefficient of transmissibility was 312,000 gallons per day per foot (gpd/ft) and the coefficient of storage was 0.12.

The storage coefficient compared favorably with the values determined in previous tests of the same aquifer (0.10 - 0.12), whereas the coefficient of transmissibility was near the lower end of the established range of values (300,000 gpd/ft - 650,000 gpd/ft). The results must be considered approximate and it was reasonable to assume that a more exhaustive test of aquifer

parameters would have provided more conclusive results.

The results of this test did indicate, however, that when the requirements for the collection of suitable data are met, the trend-surface analysis of hydrogeologic data provides additional insight into the relationship between geologic conditions and the ground water regimen and this procedure could be used for the prediction and establishment of areas of potential ground water development.

SUMMARY AND CONCLUSIONS

A trend-surface analysis of hydrogeologic data was carried out in an attempt to develop techniques which could give additional guidance in the selection of suitable areas for future ground water supplies. South Bend, Indiana was selected as an area of maximum municipal and industrial ground water requirements. Bartholomew County, Indiana was chosen as an area of essentially rural or small-scale demands. Both of these areas obtain their water supplies from sand and gravel aquifers of glacial origin in which water levels had been monitored for a period of several years.

The application of trend-surface analysis to this study was based on the premise that the piezometric or water table surface could be approximated by a mathematically computed polynomial surface of the water levels of the wells in the aquifer. The computed surface was considered to represent general, areal changes in the measured data. Deviations from this surface, termed residuals, represented localized factors influencing the measured data.

Trend-surface maps were computed from the water-level data at regular intervals and evaluated to establish their relationship with the hydrogeologic regimen. In addition, maps of the residuals from the computed surfaces were prepared and studied in conjunction with the trend maps. The maps were compared with the actual

water-table or piezometric maps drawn from the same data, with known subsurface conditions and aquifer parameters, and the fluctuation of these maps with time were compared with variations in the recharge and discharge characteristics of the ground water reservoir.

On the basis of the results obtained from these studies, the following conclusions were drawn:

For the aquifers considered, a mathematically computed surface could be considered to approximate the regional aspects of the gradient and shape of the water table or piezometric surface, minus the effects of localized factors. In this sense a trend-surface analysis of hydrogeologic data provided additional insight on factors influencing the ground water regimen. The quadratic surface proved to be the most suitable surface to work with for this purpose.

Comparison of the fluctuations of the trend-surfaces with seasonal variations in recharge and discharge illustrated the sensitivity of the computed surfaces to changes in ground water conditions. This was particularly evident in the South Bend study where the surfaces computed for the water-table aquifer adjusted much more readily to changes in recharge and discharge than the surfaces prepared from the artesian data. The actual values for the coefficient or transmissibility could not be determined in this case however.

The addition of orthogonal flow lines to the contours of the trend-surface maps provided additional information on the direction and amounts of ground water flow. In the Bartholomew County study, the direction of the orthogonal flow lines proved to reflect the relative volume of water passing through the aquifer and changes in direction of these lines indicated areas of tributary flow.

The anomalous areas of the trend-surface or residual maps represented local effects, superimposed on the regional base. These areas could be explained by a particular set of geologic hydraulic, or man-made conditions. They indicated areas where extensive recharge or discharge was centralized and could be used to evaluate the ground water conditions in these regions. In the same sense, the study of these areas facilitated the investigation of the subsurface and the influence of the geologic environment on ground water flow. The residuals were particularly useful for this effort as they were shown to reflect the hydrogeologic conditions at each control point and, when considered on a regional basis, delineated areas where geologic conditions such as aquifer thickness, lateral extent, and permeability influenced the water levels and pumping rates of the penetrating wells.

Wells producing from a multiple aquifer system or wells producing from an aquifer not associated with the aquifer under

study also could be indentified from a study of the residuals or from a study of the standard deviation from the mean value of the residuals at each control point.

Review of the results of the research illustrated that the trend-surface approach to the analysis of ground water levels cannot be fully successful unless the requirements for suitable data are satisfied. This limitation was emphasized in the South Bend study where the division of the data into two populations of wells severely restricted the validity of the conclusions that could be drawn from the analysis.

There are several requirements that must be considered in all cases. It is necessary that there are enough data collection points, in this case observation wells, to accomplish the least-squares fitting of the polynomial surfaces. These data points must be distributed over the area of investigation in such that the conclusions drawn from the analysis are truly representative of actual aquifer conditions. This requirement is difficult to meet because of the limited number of wells available for study in any given area and the bias inherent in the selection of drilling sites. In addition, the data must have been recorded at relatively short time intervals and have been maintained over a long-term period of time.

A test pumping program was carried out in Bartholomew County to evaluate the aquifer parameters of an area determined by the trend-surface analysis to be favorable for the development of ground water supplies. Although a thorough test of the aquifer could not be accomplished, the results indicated general agreement with anticipated results and it was

felt that a more exhaustive test would have substantially reinforced the conclusion drawn from the trend-surface analysis.

RECOMMENDATIONS

The problem of predicting areas for potential ground water development is becoming most important as requirements for ground water supplies increase with population and industrial growth. Current research in this field is centered around analog simulation of actual ground water conditions. However, the problem is particularly adaptable to trend-surface analysis because of the great amounts of ground water data which are continually being accumulated. The trend-surface approach has been shown to provide a rapid, inexpensive method of delineating attractive areas for detailed subsurface investigation, provided sufficient hydrologic data are available over a long term period of time. A comparison of the results derived from the trend-surface analysis with those from the analog analysis of the same area would provide much needed information on the advantages and limitations of the two procedures.

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APPENDICES

APPENDIX A

Geologic Sections

FIGURE A-1

FIGURE A-2

APPENDIX B

Representative Quadratic Surfaces, South Bend Investigation

Figure B-1 Quadratic Surface, Artesian Aquifer, April 1945

Figure B-2 Quadratic Surface, Water Table Aquifer, April 1945

Figure B-3 Quadratic Surface, Artesian Aquifer, July 1945

Figure B-4 Quadratic Surface, Water Table Aquifer, July 1945

Figure B-5 Quadratic Surface, Artesian Aquifer, October 1945

Figure B-6 Quadratic Surface, Water Table Aquifer, October 1945

Figure B-7 Quadratic Surface, Artesian Aquifer, January 1946

Figure B-8 Quadratic Surface, Water Table Aquifer, January 1946

Figure B-9 Quadratic Surface, Artesian Aquifer, April 1946

APPENDIX C

**Quadratic Surfaces and Residuals,
Bartholomew County Investigation**

Figure C-1

Quadratic Surface, October 1965

Figure C-2 Residuals from Quadratic Surface, October 1965

Figure C-3 Quadratic Surface, November 1966

Figure C-5 Quadratic Surface, May 1967

APPENDIX D

Test Well Data

GAMMA RAY LOG OF OBSERVATION WELL DRILLED FOR PUMPING TEST

BAKALAR AIR FORCE BASE, INDIANA

AUGUST 16, 1967

FIGURE D-1

☒ TEST Observation

INDIANAPOLIS • MISHAWAKA • LANSING

☐ PERMANENT

Job No. C-21087

WELL LOG No. 67B CITY Columbus

County Bartholomew

Owner Purdue Civil Engineering School

Township Columbus

Section 6, T10N, R6E

Location Bakalar Air Force Base

State Indiana

From Land Description

From Street or Road 2,000' W. of Co. Rd. No. 100E 50' N. of Co. Rd. 300N

[illegible]

Hole 5 "Die Drilled by: { Cable Tool _____ Rotary X Jetting _____
Reverse Circ. _____ Bucket _____ Auger _____

Rotary Hole Grouted: Neat Cement _____ Drilling Mud _____ Other _____

Casing 2-1/2" OD From 24' above ground to 76' feet below ground. Weight _____ Pounds per foot

Screen 2 " Set from 76 to 79 feet Make steel Type _____ Slot 0.050

Pumping test No GPM drawdown to _____ feet after _____ hours pumping

Date Completed 8-2-67 Driller Leon English

NORTHERN COMPANY
INCORPORATED

INCORPORATED

INDIANAPOLIS • MISHAWAKA • LANSING

☒ TEST

☐ PERMANENT

Job No. C-21087

WELL LOG No. 67A CITY Columbus

County Bartholomew

Owner Purdue Civil Engineering School

Township Columbus

Section Sec. 6 T10N R6E

Location Bakalar Air Force Base

State Indiana

From Land Description

From Street or Road 2,000' W. of Co. Rd. No. 100E, 150' N. of Co. Rd. 300N,

100' N. of Observation Hole No. 67B

[illegible]

Hole 8 "Dia Drilled by: { Cable Tool _____ Rotary X Jetting _____ Note: Casing & screen removed after test.
Reverse Circ. _____ Bucket _____ Auger _____

Rotary Hole Grouted; Neat Cement _____ Drilling Mud _____ Other _____

Casing 8 " ^{I.D.}~~OD~~ from 12 " above ground to 58 feet below ground. Weight _____ Pounds per foot

Screen 80.0 " Set from 58 to 78 feet Make Layne type steel slot 0.070

Pumping test 275 GPM drawdown to 53 feet after 20 hours pumping

Date Completed 8-4-67 Driller Leon English

PAGE NO. 1 OF 3

INDIANAPOLIS • MISHAWAKA • LANSING

Date 8-8 19 67

PRODUCTION TEST OF WELL

Job No. C-21087

Owner Purdue University City Columbus State Indiana
 Well No. 67A Location Bakalar A.F.B. also show sketch on back
 Measured from Ground Level: Total Depth 78' Inside Dia. 8" Standing Water Level 15'
 Type Well: Gravel Wall Tubular X Rock New X Old Cleaned Gravel Wall Dia
 Screen: Length 20' Dia. 8" Slot Size 0.070 type shutter Depth to Top 58'
 Driven by Electric () Engine (x) Pump Bowl Layne Stages 4
 Length Suction Pipe Well top to bottom of Suction 70'
 Orifice Size 6 by 4 Water discharged 35 feet from well into run off
 Well top to bottom of air line 65' Gauge reads feet (x) pounds ()

DATE	TIME	INCHES ON ORIFICE	GALLONS PER MINUTE	AIR LINE READING	GROUND TO WATER LEVEL	DISCHARGE PRESSURE	REMARKS
8-7-67	10:00 a.	19	278		52'		start of test
	10:11	18.5	275		53		water clear
	10:12	18.5	275		53.5		
	10:20	18.5	275		53.5		
	10:30	18.5	275		53.5		
	10:40	18.5	275		53.5		
	10:50	18.5	275		53.5		
	11:00	18.5	275		53.5		
	11:30	18.5	275		53.5		
	12:00	18.5	275		53.5		
	12:30 p.	18.5	275		53.5		
	1:00	18.5	275		53.5		
	1:30	18.5	275		53.5		
	2:00	18.5	275		53.5		
	2:30	18.5	275		53.5		
	3:00	18.5	275		53.5		
	3:10	18	271		52.5		
	3:30	17.5	268		52		
	3:45	17.5	268		52		
	4:00	17.5	268		52		
	4:30	17.5	268		52		
	5:00	17.5	268		52		
	5:10	17.5	268		52		
	5:15	18.5	275		52.5		
	5:20	18.5	275		53		
	5:30	18.5	275		53		

State fully any details on back of this sheet. Water temperature near end of test °F
 Tested and Witnessed by

FOR LAYNE-NORTHERN COMPANY, INC.

Witnessed by For Purchaser.

PAGE NO. 2 OF 3

-NORTHERN COMPANY, INC.

INDIANAPOLIS • MISHAWAKA • LANSING

Date 8-8 19 67

PRODUCTION TEST OF WELL

Job No. _____

Owner Purdue University City _____ State _____

Well No. _____ Location _____ also show sketch on back

Measured from Ground Level: Total Depth _____ Inside Dia. _____ Standing Water Level _____

Type Well: Gravel Wall _____ Tubular _____ Rock _____ New _____ Old _____ Cleaned _____ Gravel Wall Dia. _____

Screen: Length _____ Dia. _____ Slot Size _____ Type _____ Depth to Top _____

Driven by Electric () Engine () Pump Bowl _____ Stages _____

Length Suction Pipe _____ Well top to bottom of Suction _____

Orifice Size _____ by _____ Water discharged _____ feet from well into _____

Well top to bottom of air line _____ Gauge reads feet () pounds ()

DATE	TIME	INCHES ON ORIFICE	GALLONS PER MINUTE	AIR LINE READING	GROUND TO WATER LEVEL	DISCHARGE PRESSURE	REMARKS
	6:00	18.5	275		53.5		
	6:30	18.5	275		53.5		
	7:00	18.5	275		53.5		
	7:30	18.5	275		53.5		
	8:00	18.5	275		53.5		
	8:30	18.5	275		53.5		
	9:00	18.5	275		53.5		
	9:30	18.5	275		53.5		
	10:00	18.5	275		53.5		
	10:30	18.5	275		53.5		
	11:00	18.5	275		53.5		
	11:30	18.5	275		53.5		
	12:00	18.5	275		53.5		
8-8-67	1:00 a.	18.5	275		53.5		
	2:00	18.5	275		53.5		
	3:00	18.5	275		53.5		
	3:30	18.5	275		53.5		
	4:00	18.5	275		53.5		
	4:30	18.5	275		53.5		
	5:00	18.5	275		53.5		
	5:30	18.5	275		53.5		
	6:00	18.5	275		53.5		
	6:30	18.5	275		53.5		
	7:00	18.5	275		53.5		
	7:02	24.5	314		61	increased	rate of
	7:05	25.5	320		62	pumpage	

State fully any details on back of this sheet. Water temperature near end of test _____ °F
 Tested and Witnessed by _____

FOR LAYNE-NORTHERN COMPANY, INC.

Witnessed by For Purchaser. _____

INDIANAPOLIS • MISHAWAKA • LANSING

Date 8-8 1967

PRODUCTION TEST OF WELL

Job No.

Owner Purdue University City _____ State _____
Well No. _____ Location _____ also show sketch on back
Measured from Ground Level; Total Depth _____ Inside Dia. _____ Standing Water Level _____
Type Well: Gravel Wall _____ Tubular _____ Rock _____ New _____ Old _____ Cleaned _____ Gravel Wall Dia. _____
Screen: Length _____ Dia. _____ Slot Size _____ Type _____ Depth to Top _____
Driven by Electric () Engine () Pump Bowl _____ Stages _____
Length Suction Pipe _____' Well top to bottom of Suction _____
Orifice Size _____ by _____ Water discharged _____ feet from well into _____
Well top to bottom of air line _____ Gauge reads feet () pounds ()

State fully any details on back of this sheet. Water temperature near end of test °F
Tested and Witnessed by

Witnessed by For Purchaser.

Leupold & Stevens Instruments, Inc., Portland, Ore.

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