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PRELIMINARY EVALUATION OF GROUND-WATER CONTAMINATION BY COAL-TAR DERIVATIVES, ST. LOUIS PARK AREA, MINNESOTA

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CONVERSION FACTORS

Multiply inch-pound units	By	To obtain SI units
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
foot per day (ft/day)	0.3048	meter per day (m/day)
foot squared per day (ft^2/day)	0.0929	meter squared per day (m^2/day)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

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ABSTRACT

Operation of a coal-tar distillation and wood preserving plant from 1918-72 in St. Louis Park, a suburb of Minneapolis, Minnesota, resulted in ground-water contamination. This preliminary evaluation presents an overview of the problem based on the results of the first year (1979) of an ongoing study.

By 1932, water in the Prairie du Chien-Jordan aquifer, the region's major source of ground water, was contaminated 3,500 feet from the plant. It seems that this early contamination of the aquifer resulted in part from the introduction of coal-tar directly into a multiaquifer well on the plant site. The Prairie du Chien-Jordan aquifer underlies the area at depths of 250 to 500 feet and is overlain by two bedrock aquifers (Platteville and St. Peter), two confining beds (Glenwood and the basal part of St. Peter), and 70 to 100 feet of drift.

The upper part of the Prairie du Chien aquifer is carbonate rock having fracture and solution-channel permeability, and low effective porosity. Contaminants in the Prairie du Chien Group can move more rapidly than those in drift and sandstone aquifers that have intergranular permeability. The aquifer characteristics, the long contamination history, and seasonal potentiometric surface fluctuations owing to heavy municipal and industrial withdrawals combine to create a complex distribution of coal-tar derivatives in the Prairie du Chien-Jordan aquifer.

In addition, at least 25 ungrouted or partly cased wells in the area may permit contaminated water from near-surface aquifers to flow downward into deeper bedrock aquifers along or through the well bores. Where possible, such wells have been geophysically logged and inspected by downhole television. Flow rates of 20 to 150 gallons per minute from the Platteville and St. Peter aquifers to the Prairie du Chien-Jordan aquifer were observed in five of nine wells. The water was contaminated in four of the wells.

Drift materials on and south of the site have been contaminated by surface spills and by infiltration of contaminated process water. Near the contamination source, a hydrocarbon fluid phase is moving vertically downward relative to movement of the aqueous phase. Fluid pumped from a monitoring well in this area contained 6,000 milligrams per liter total organic carbon. Dissolved coal-tar constituents in the drift and the uppermost bedrock unit over most of the area, the Platteville aquifer, have moved at least 4,000 feet downgradient to a drift-filled bedrock valley. There it seems that the Platteville aquifer and the Glenwood confining bed have been removed by erosion and that contaminants with a concentration of approximately 2 milligrams per liter dissolved organic carbon are entering the underlying St. Peter aquifer. Chemical analysis of

fluid pumped from monitoring wells suggests that soluble, low-molecular-weight compounds are moving preferentially through the drift-Platteville aquifer system.

INTRODUCTION

Between 1918 and 1972, a coal-tar distillation and wood-preserving plant operated on an 80-acre site in St. Louis Park, a suburb of Minneapolis, Minn. Release of coal-tar derivatives to the environment has resulted in contamination of drift and bedrock aquifers.

The major immediate problem is the presence of toxic coal-tar derivatives in water withdrawn by some municipal wells in the area. As early as 1932, the Prairie du Chien-Jordan aquifer, the principal ground-water resource of the Minneapolis-St. Paul metropolitan area, contained water with a coal-tar taste at least 3,500 feet from the site. During 1978, use of four municipal wells completed in this aquifer was discontinued because the wells yielded water containing trace amounts of coal-tar compounds, including benzo(a)pyrene, a carcinogen. Each of the five bedrock aquifers in the metropolitan area underlies the site, and each may have been affected to some degree by the contaminants.

The complicated ground-water hydrology, the diverse chemical and physical properties of coal-tar constituents, and the length of time the contaminants have been moving through the ground-water system, have combined to produce a complex distribution of contaminants.

Individual coal-tar compounds differ widely in toxicity and chemical and physical properties. For example, phenol is about 10 million times more soluble in water than benzo(a)pyrene. Differences in solubility cause large variations in the proportion of each chemical that remains in a mixture of liquid hydrocarbons, dissolves into the ground water, or is sorbed onto geologic materials. The proportions change with chemical concentration, in space, and with time.

The health risks associated with long-term exposure to low concentrations of coal-tar compounds are poorly known. Moreover, the original coal-tar constituents can be changed into other compounds through chemical reactions and biological processes. These compounds have not yet been identified.

Coal-tar derivatives reached the water table by percolation through the unsaturated zone (see glossary) and at ponds that received surface runoff and process water from the plant. The highest concentrations of contaminants are in the drift beneath and near the site. Parts of this volume of drift contain an undissolved liquid mixture of many individual coal-tar compounds. In the saturated zone (see glossary), this hydrocarbon fluid phase has moved vertically downward relative to the direction of ground-water flow because it is denser than water. Because the hydrocarbon fluid is more viscous than water, it moves more slowly than the ground water that surrounds it.

Uncontaminated ground water entering the volume of drift near the site is contaminated by partial solution of the hydrocarbon fluids and by release of compounds sorbed on the drift materials. The contaminated water moves laterally to the east and southeast. Water in the drift 4,000 feet east of the site has a distinct chemical smell and contains a large proportion of coal-tar compounds of high solubility relative to compounds of low solubility.

Contaminants have moved into the uppermost bedrock aquifer (Platteville) directly from the drift. They have reached deeper bedrock aquifers through wells that hydraulically interconnect aquifers and probably through a confining bed, and through bedrock valleys where this confining bed (Glenwood) has been removed by erosion. In addition, coal tar has entered the bedrock aquifer system directly through a well on the former plant site that was drilled in 1917 to a depth of 909 feet.

The bedrock ground-water flow system is continually adjusting to hydraulic stresses such as ground-water withdrawals and flow through wells that connect more than one aquifer. As these stresses change, the direction and rate of contaminant transport change. Consequently, the concentration and composition of contaminants in water pumped from individual industrial and municipal wells fluctuates with time.

Purpose and Scope

On July 1, 1978, the U.S. Geological Survey began a study of the St. Louis Park problem in cooperation with the Minnesota Department of Health. Its purpose is to develop a detailed understanding of the ground-water flow system and the transport of organic contaminants in the vicinity of the former plant. Results of the study will be used to guide management decisions by State and local agencies.

This report is based on the results of the first year of study. The purpose of the report is to evaluate the problem in a preliminary way and to make some of the collected data available. Because the problem is complex, the data are not interpreted in detail. The interpretations presented are preliminary and doubtless will be changed as additional field data are collected and working hypotheses are tested.

Future reports will further interpret data presented in this report and will present the results of laboratory experiments to assess the mobility of coal-tar derivatives in ground water, preliminary digital-computer simulations of the ground-water system, and additional fieldwork.

Location and Description of Study Area

The site of the former coal-tar plant is in the city of St. Louis Park, Hennepin County, Minn. (fig. 1). The city adjoins Minneapolis on the east and the cities of Golden Valley, Minnetonka, Hopkins, and Edina on the north, west, south, and southeast, respectively (fig. 2).

In this report, the term "site" refers to the approximately 80-acre tract on which the plant was located. The term "study area" refers to the geographic extent of the ground-water system that will be evaluated in this project. The study area is underlain by drift and five bedrock aquifers. The areal extent

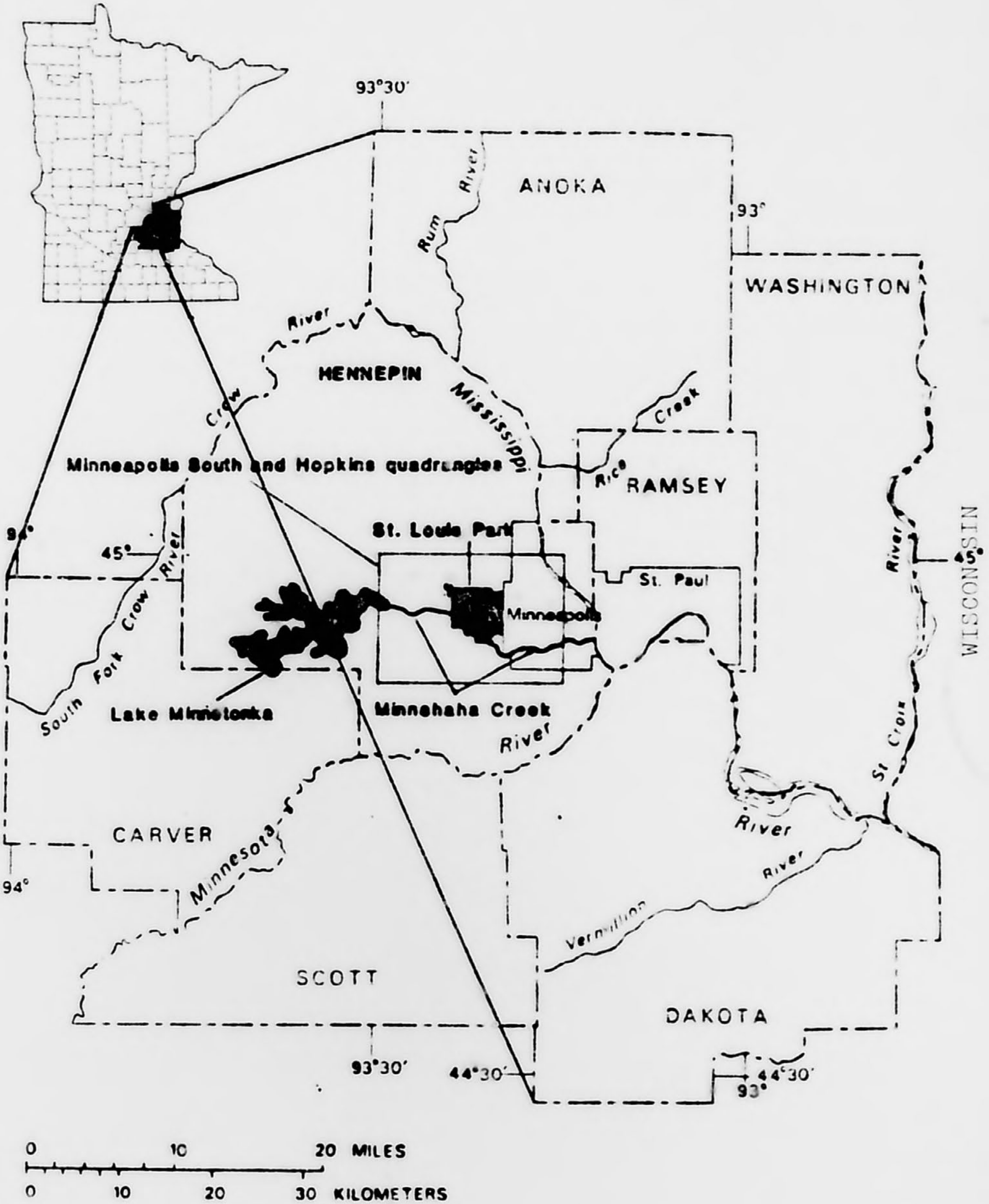


Figure 1.--Location of the city of St. Louis Park, the Minneapolis South and Hopkins quadrangles, Lake Minnetonka, and Minnehaha Creek in the Minneapolis-St. Paul metropolitan area

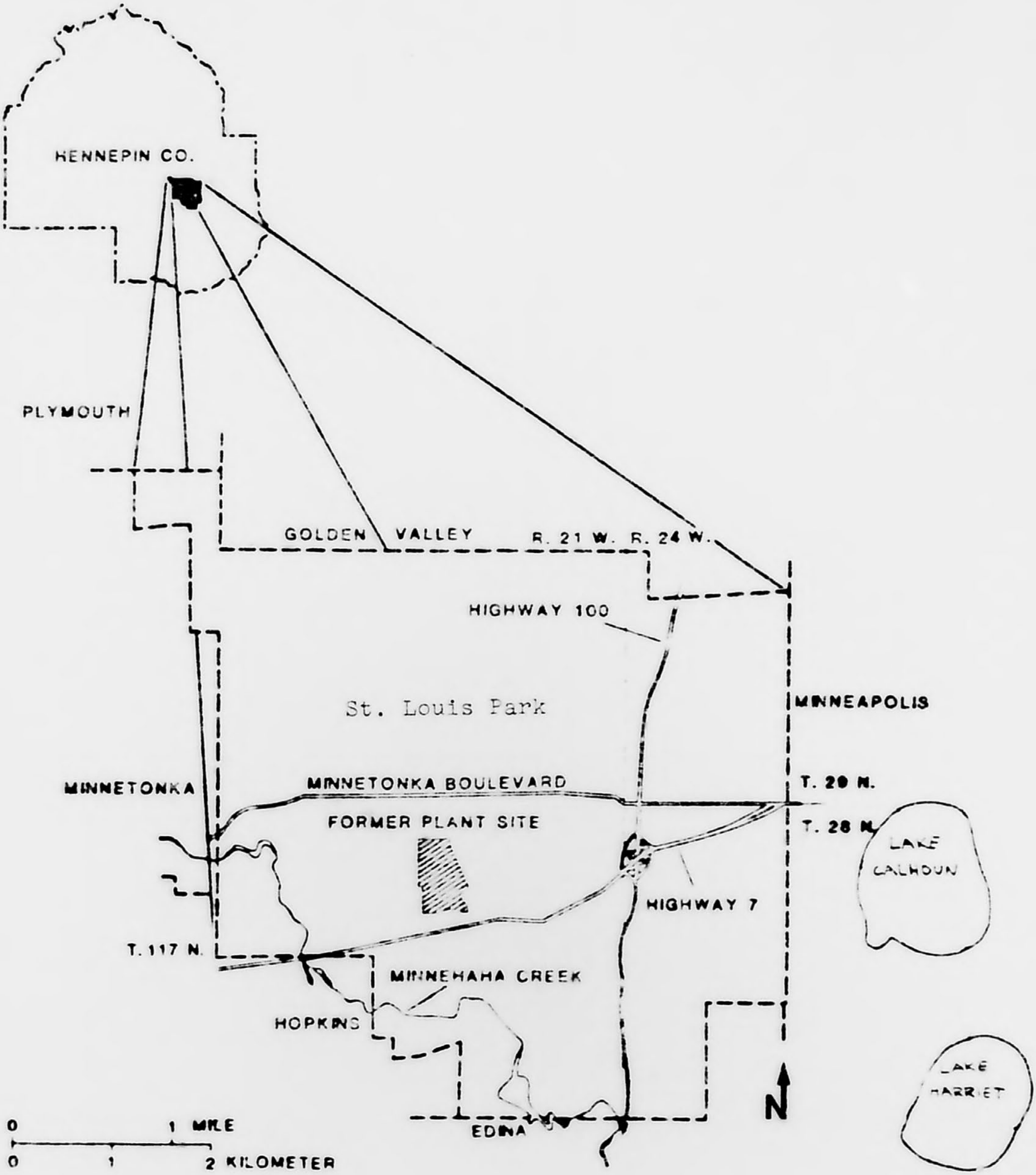


Figure 2.-- Site of former plant in St Louis Park, Minnesota

of contamination and location of significant hydrogeologic boundaries is different for each aquifer. Therefore, the amount and kinds of geologic, hydrologic, and chemical data required to evaluate the contamination problem vary both areally and with depth in the ground-water system.

A ground-water-flow model of the seven-county Minneapolis-St. Paul metropolitan area is at present (1979) being developed by the U.S. Geological Survey in cooperation with the Metropolitan Council of the Twin Cities, the Minnesota Geological Survey, and Minnesota Department of Natural Resources. Preliminary results of this project are being used to assess the location and nature of hydrogeologic boundaries in the bedrock aquifer system that will be used to define the study area for the St. Louis Park study. Tentatively, the study area for bedrock aquifers below the Platteville aquifer is the area between Lake Minnetonka on the west, the Minnesota and Mississippi Rivers on the south and east, and approximately lat 45° on the north (fig. 1). The area being studied in the drift and uppermost bedrock aquifer is bounded by Minnehaha Creek on the west and south, Lake Calhoun and Lake Harriet to the east, and Minnetonka Boulevard to the north (fig. 2).

Previous Investigations and History of Reported Contamination

The coal-tar plant began operation in 1918 on the site of a former sugar-beet processing plant. In 1932, the first St. Louis Park municipal well was constructed. After several weeks of operation, complaints of a coal-tar taste to the water caused the well to be shut down. The well, Old St. Louis Park well 1, (W112; table 1, fig. 3, and pl. 1) is completed in the Prairie du Chien-Jordan aquifer about 3,500 feet from the plant site. Attempts at reconstructing the well to eliminate the contamination were unsuccessful, and the well was abandoned in 1933. Water-quality changes in this well have not been monitored, but since 1953 water levels in in the well have been recorded by the U.S. Geological Survey.

An investigation by the McCarthy Well Company in 1933 (files of the U.S. Geological Survey) concluded that the contaminants were coming from the site through "several old wells that were being used to drain creosote away into the ground." One old well on the site (W105; table 1 and fig. 3) was drilled to an original depth of 940 feet (Fuller, 1904). It has also been reported (Barr, 1977) that contamination of another well, W23, (table 1, fig. 3, and pl. 1) resulted from a spill into the well, possibly from a railroad tankcar in about 1930. Well W23 (referred to in Barr (1977) as "Hinckley well on the site") was drilled in 1917 to an original depth of 909 feet.

A report by the Minnesota Department of Health (1938) identified nine wells that yielded water with either a phenolic or tar-like taste. The well farthest from the site, W114, (table 1, fig. 3, and pl. 1) was originally completed at a depth of 280 feet in the St. Peter aquifer (Schwartz, 1936). In 1936, the well was deepened by drilling an additional 130 feet. After reconstruction, the well was open to the Prairie du Chien-Jordan aquifer and immediately yielded water with a distinct tarlike taste.

Numerous engineering and hydrogeologic studies have been made to examine various aspects of the problem. E. A. Hickok and Associates (1969) reported that the phenolic concentration in water measured in 1946 from St. Louis Park well 4, completed in the Prairie du Chien-Jordan aquifer, was 0.10 mg/L (pl. 1). Measurements in 1969 indicated possible contamination of other wells and the Hickok report suggested that additional studies be made to better evaluate the problem.

Sunde (1974), in a general evaluation of the problem, concluded that contamination in the deeply buried bedrock aquifers resulted from flow through wells that connect more than one aquifer. The Minnesota Department of Health (1974) tested the water quality of private, industrial, and municipal wells in the area. Olson and others (1974) compiled available geologic information on the St. Louis Park area. National Biocentric (1976a; 1976b) chemically analyzed drift materials underlying the northern part of the site for organic contaminants.

Barr Engineering Co. (1976; 1977) installed 3 piezometers and 14 drift and 2 bedrock monitoring wells. Cores from 14 borings were analyzed for phenolic and benzene-extractable compounds. Data from the borings were used to estimate that removal of drift contaminated with more than 1,000 mg/kg of benzene-extractable constituents would require excavation of 400,000 cubic yards of soil. Water samples were analyzed for phenolic compounds, oil and grease, and selected inorganic constituents. Water in the drift was found to be contaminated at least 1,000 feet from the site. Specific remedial actions were recommended to control ground-water contamination in the drift. Barr concluded that the low but detectable levels of phenolic compounds in municipal wells completed in the Prairie du Chien-Jordan aquifer could not be explained by the available data.

The Minnesota Department of Health (1977; 1978) measured the concentration of polynuclear aromatic hydrocarbons (PAH) in municipal water supplies, assessed the health-risk implications, and outlined major additional data needs. Plate 1 shows the location of municipal wells in the Prairie du Chien-Jordan aquifer that were found to be contaminated and bar graphs of the concentration of individual PAH constituents.

In February 1979, the U.S. Geological Survey concluded an initial field study and evaluation of the effect of multiaquifer wells. Data on the location and construction of wells in the area were provided to the Minnesota Department of Health. These data were used by the department to design and implement a well-abandonment program.

Well-Numbering System

Each well or test hole has been assigned four identifying numbers. They are (1) WATSTORE (STORET) site identification, (2) township and range location, (3) Minnesota Unique Well Number, and (4) a project number (table 1).

WATSTORE and STORET are water-quality data bases maintained by the U.S. Geological Survey and U.S. Environmental Protection Agency, respectively. Most data in WATSTORE can be obtained through STORET. The WATSTORE site identification number is identical to the STORET station number and is needed to enter data into either of these data bases. The first six numerals of the number are the latitude of the well location in degrees, minutes, and seconds. The next seven numbers are the longitude of the location. The last two numbers are arbitrary sequence numbers, which distinguish wells within a given one-second by one-second area (approximately 75 by 100 feet).

The township and range method of numbering test holes and wells is based on the U.S. Bureau of Land Management's system of subdivision of public lands (fig. 2). The first segment of a well or test-hole number indicates the township north of the baseline; the second, the range west of the principal meridian; and the third, the section in which the well is situated. The letters A, B, C, and D, following the section number, indicate well location in the section. The first letter denotes the 160-acre tract, the second letter the 40-acre tract, and the third letter the 10-acre tract. The letters are assigned counterclockwise beginning with the northeast quarter. Consecutive numbers beginning with 1 are added as suffixes to distinguish wells within a given 10-acre tract. For example, the number 117.21.17BAC2 identifies the second well or test hole in the SW NE NW , sec. 17, T. 117 N., R. 21 W.

The Minnesota Unique Well Number is an arbitrary sequence number assigned by the State of Minnesota to new wells when they are drilled and older wells when they are located in the field. This number is needed to identify wells in ground-water data bases maintained by the State.

The project well number is used throughout this report to identify wells and piezometers. Municipal-supply wells are numbered with the initial letters of the name of the municipality and the well number assigned to the well by the municipality. For example, St. Louis Park municipal well 4 is numbered SLP4. Other wells, piezometers, and borings are numbered with the prefix W, P, or B, respectively, and a sequence number. Wells W1-W17 and piezometers P1-P3 are consistent with the numbering system used in Barr (1976; 1977).

Glossary

The geologic, hydrologic and chemical terms pertinent to this report are defined as follows:

Aqueous phase - water in the saturated or unsaturated zone, which may contain hydrocarbon compounds (see Hydrocarbon fluid phase; Hydrocarbon solid phase).

Aquifer - a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Confined ground water - ground water under pressure significantly greater than atmospheric. Its upper limit is the bottom of a bed of distinctly lower vertical hydraulic conductivity than that of the material in which the confined water occurs. (See "Confining bed.")

Confining bed - a body of material with low vertical permeability stratigraphically adjacent to one or more aquifers. Replaces the terms "aquiclude," "aquitard," and "aquifuge."

Constituent, coal-tar - a chemical compound identified as occurring in significant amounts in commercial coal-tar. (See "Derivative, coal-tar" and "Degradation product, coal-tar").

Degradation product, coal-tar - a chemical compound identified as being formed by chemical or biochemical reactions involving coal-tar constituents.

Derivative, coal-tar - a constituent or degradation product of coal tar. (See "Constituent, coal-tar" and "Degradation product, coal-tar").

Desorption - the removal of contaminants from the solid matrix of the porous medium by fluids in the ground-water system.

Diffusion - molecular movement of chemical constituents of ground-water or hydrocarbon fluids in response to chemical-concentration gradients.

Dispersion, mechanical - differences in the rate and direction of movement of individual tracer particles owing to variations in path lengths, and pore geometry or size.

Dispersion, hydrodynamic - the combined effects of "Diffusion" and "Dispersion, mechanical."

Dissolved - organic or inorganic constituents of ground water that are not removed by filtration through a 0.45 micron filter. (See "Suspended" and "Total.")

Drawdown - the vertical distance between the static (nonpumping) water level and the level caused by pumping.

Drift - all deposits resulting from glacial activity.

Ground water - that part of subsurface water that is in the saturated zone.

Head, static - the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity - capacity of a rock to transmit water under pressure. It is the rate of flow of water at the prevailing kinematic viscosity passing through a unit section of area, measured at right angles to the direction of flow, under a unit hydraulic gradient (see "Permeability, intrinsic").

Hydrocarbon fluid phase - a liquid mixture of hydrocarbon compounds, immiscible with water, that forms a fluid phase physically distinct from the aqueous phase. It is distinctly denser and more viscous and has a higher surface tension than the aqueous phase. (See Aqueous phase; Hydrocarbon solid phase.)

Hydrocarbon solid phase - hydrocarbon compounds sorbed onto the matrix of the porous media. (See Aqueous phase; Hydrocarbon fluid phase; Sorption.)

Isopotential line - line connecting points of equal static head. (Head is a measure of the potential.)

Multiaquifer well - any well that hydraulically connects more than one aquifer. The connection may be due to original open-hole construction or to deterioration of casing or grout seal.

Outwash - sorted, stratified drift deposited beyond the ice front by meltwater streams.

Permeability, intrinsic - a measure of the relative ease with which a porous medium can transmit liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. It is a property of the medium that is dependent upon the shape and size of the pores.

Piezometer - a small-diameter pipe placed in the ground in such a way that the water level in the pipe represents the static head at the very point in the flow field where the piezometer terminates.

Porosity - the property of a rock or soil to contain interstices or voids. It may be expressed quantitatively as the ratio of the volume of interstices to total volume of the rock. (See "Porosity, effective.")

Porosity, effective - the amount of interconnected pore space available for fluid transmission. It is expressed as a decimal fraction or as a percentage of the total volume occupied by the interconnecting interstices.

Potentiometric surface - a surface that represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. Where the head varies appreciably with depth in the aquifer, a potentiometric surface is meaningful only if it describes the static head along a particular specified surface or stratum in that aquifer. More than one potentiometric surface is then required to describe the distribution of head. The water table is a particular potentiometric surface. Replaces the term "Piezometric surface."

Saturated zone - zone in earth's crust in which all voids are ideally filled with water. The water table is the upper limit of this zone. Water in the saturated zone is under pressure equal to or greater than atmospheric.

Sorption - the removal of contaminant from fluids in the ground-water system by the solid matrix of the porous medium.

Specific capacity - the rate of discharge of water from a well divided by the drawdown of water level within the well. It varies slowly with duration of discharge, which should be stated when known. If the specific capacity is constant except for time variation, it is roughly proportional to the transmissivity of the aquifer.

Specific yield - the ratio of the volume of water that a saturated rock or soil will yield by gravity to its own volume.

Storage coefficient - the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is virtually equal to the specific yield.

Suspended - organic or inorganic constituents of ground water that are removed by filtration through a 0.45 micron filter. (See "Dissolved" and "Total.")

Till - unsorted, unstratified drift deposited directly by the ice.

Transmissivity - the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Total - with reference to chemical constituents in ground water, the amount of the chemical constituent in an unfiltered sample. (See "Dissolved" and "Suspended".)

Unconfined ground water - water in an aquifer that has a water table.

Valley fill - drift or alluvial sediments deposited in an erosional depression in the bedrock surface.

Water table - that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells that penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

Well field - as used in this report, any combination of wells withdrawing water from the same area and close enough to cause mutual drawdown effects.

Zone, saturated - that part of the water-bearing material in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric. The saturated zone may depart from the ideal in some respects. A rising water table may cause entrapment of air in the upper part of the zone of saturation, and some parts may include accumulations of other fluids.

Zone, unsaturated - the zone between the land surface and the water table. It includes the capillary fringe. Characteristically, this zone contains liquid water under less than atmospheric pressure and water vapor and air or other gases generally at atmospheric pressure. In parts of the zone, interstices, particularly the small ones, may be temporarily or permanently filled with water. Perched water bodies may exist within the unsaturated zone and some parts may include accumulations of other fluids. Replaces the terms "zone of aeration" and "vadose zone."

Acknowledgments

The authors are grateful to area residents and businesses for their continuing cooperation in this study. The assistance of E. H. Renner and Sons Well Drilling Co. has been especially useful in locating old wells. Discussions with the numerous hydrologists and engineers that have been professionally associated with the problem have provided valuable insight into the factual, technical, and scientific issues involved. Particular thanks are given Mr. Richard Koppy and Mr. Vernon Tollefsrud of the city of St. Louis Park, Department of Public Works, for their efforts to expedite this study, and to Mr. William Scrutin, Minnesota Department of Health, for the diligence and timeliness of his work in developing procedures for the isolation and measurement of chemical constituents.

HYDROGEOLOGY

Contaminants move through the ground-water system primarily as a result of the movement of ground water. Movement of ground water is controlled by the geometry and hydraulic characteristcs of rock units and the distribution of hydraulic head. The hydrogeologic system is continuously recharged in some places and discharged in others. It is always tending to adjust, sometimes in minor degrees, to climatic variations and the activities of man. As the system responds to these changes, the direction and rate of contaminant movement may change. The purpose of the hydrogeologic investigation is to develop an understanding of how the ground-water system operates, and how future activities of man, including possible remedial actions, may affect contaminant movement.

Bedrock Geology

Bedrock geology maps included in this report are preliminary versions of maps that will be updated and modified for use by the U.S. Geological Survey in constructing a numerical model of the ground-water flow system in the seven-county Minneapolis-St. Paul metropolitan area. As part of that modeling project, the Minnesota Geological Survey, in cooperation with the U.S. Geological Survey, is preparing structure-contour and thickness maps for 10 bedrock units.

The amount of geologic detail required for the St. Louis Park study is greater than that required for the metropolitan area project. Consequently, more detailed geologic maps of the Minneapolis South and the Hopkins 7 1/2-minute quadrangles (fig. 1) have been prepared by the U.S. Geological Survey for this study.

Water-well and test-hole records, and data plots were obtained from the Minnesota Geological Survey and the files of the U.S. Geological Survey and compiled at a scale of 1:24,000. The bedrock geology map (fig. 4) and bedrock topography map (fig. 5) were constructed from these data and from maps previously prepared by the U.S. Geological Survey and Minnesota Geological Survey. The northeastern part of the mapped area is generalized from Norvitch and Walton (1979). An unpublished map of the Hopkins quadrangle prepared by the Minnesota Geological Survey was updated with additional information, and a consistent map covering both quadrangles was prepared.

Figures 4 and 5 are in nearly final form, with the exception of the area near the site. A 40-foot contour interval is used in the structure-contour maps of hydrogeologic units below the St. Peter aquifer (pl. 2) to indicate general structural trends.

Mapping of subsurface geologic features requires interpolation between discreet data points, generally geologic or geophysical logs of wells or test holes. If the structure being mapped is simple, such as the top of a uniformly dipping, distinct strata, relatively few data points are required to produce a map acceptable for most purposes. The structure-contour map of the top of the Mount Simon-Hinckley aquifer (pl. 2) is an example of such a map. The reliability of a map can be generally assessed by the amount of change required to make the map consistent with new or independent data. In the example of the map of the top of the Mount Simon-Hinckley aquifer, additional data will doubtless result in some changes of the contours. These refinements, however, will not be critical to understanding the contamination problem.

In contrast with the simple geometry of the top of the Mount Simon-Hinckley aquifer, the configuration of the bedrock surface near the site (pl. 2) is complex. Considerable detail will be required for an adequate understanding of the local hydrogeology. New data from the ongoing study may result not in minor refinements, but, rather, in substantial revisions of the present interpretation.

Data used in preparation of this map are from,

1. Water-well and test-hole information from the files of the U.S. Geological Survey and Minnesota Geological Survey
2. Test holes and wells installed for this study
3. Water-well records obtained from drillers
4. Test holes and monitoring wells installed in conjunction with the construction of Louisiana Ave
5. Seismic surveys by the U.S. Geological Survey
6. Previous reports (principally Schwartz, 1936; Barr, 1977)
7. Geophysical logging of wells by the U.S. Geological Survey

Because of the potential confusion caused by incomplete well logs, wells are being geophysically logged, where possible, to confirm the reported stratigraphy. For wells at critical locations, attempts were made to obtain more complete logs than those available in the files of the Minnesota Geological Survey and U.S. Geological Survey. Data on file and previously reported by

Barr (1977) indicated that the well at Methodist Hospital (W48) penetrated the full thickness of St. Peter Sandstone but that the Platteville Limestone and Glenwood Shale were absent. Daily drilling records from the driller, however, indicate that 9 feet of "broken lime rock and gravel" (Platteville) overlie the sandstone. Similarly, the log on file for the Milwaukee Railroad well (W38) did not record the Platteville and Glenwood, but a published log for the well (Schwartz, 1936) indicates that 4 feet of limestone overlies the St. Peter.

The distribution of the Glenwood confining bed is of major importance in the transport of contaminants near the site. Regionally, leakage through the unit is significant, but locally it impedes ground-water flow and transport of contaminants. The unit separates the Platteville and St. Peter aquifers and includes the Glenwood Shale of Ordovician age and the upper part of the St. Peter Sandstone of Ordovician age.

The Glenwood Shale is thin, and is commonly not recorded in water-well logs. At wells where the overlying Platteville Limestone is reported as the uppermost bedrock unit, evaluation of the reported data is simple and unambiguous. However, logs for several wells indicate that the underlying St. Peter Sandstone of Ordovician age is the uppermost bedrock unit and that the altitude of the bedrock surface corresponds to that of uneroded St. Peter Sandstone. Locally, this condition may exist because of in-situ chemical weathering and subglacial scouring. In general, however, this interpretation of the bedrock surface is inconsistent with observations of the geomorphology of stream-eroded channels through these rocks where they are exposed elsewhere in the area. Typically, the Platteville Limestone forms a protective caprock, the Glenwood Shale a reentrant in the valley wall, and the St. Peter Sandstone a near-vertical bluff. Commonly, there is a talus slope of reworked St. Peter Sandstone armoured with blocks of Platteville Limestone at the base of the exposure.

Four major geomorphic processes may be responsible for the relief on the bedrock surface near the site: (1) Stream erosion, (2) subglacial plucking and abrasion, (3) subglacial stream erosion, and (4) in-situ chemical weathering. Each mechanism can produce an erosional surface with a distinctive geometry.

The bedrock geology maps (figs. 4, 5, and pl. 2) are drawn on the assumption that stream erosion is responsible for the major depressions in the bedrock surface. Because streams have graded longitudinal profiles, this interpretation requires that the bedrock valleys have similar, graded profiles. In southeastern Minnesota, where the Platteville Limestone is not covered by thick drift, narrow valleys having dendritic patterns have formed by waterfall recession. Olson and others (1974), however, suggest that the bedrock valleys in the St. Louis Park area were formed during glacial periods by streams that formed in front of the glacier margin (proglacial streams). Valleys that may have been eroded by preglacial or proglacial streams in the St. Louis Park area may also have been substantially modified by plucking and abrasion beneath the glaciers.

Wright (1973) has shown that moving water beneath active Pleistocene glaciers cut valleys into the bedrock surface elsewhere in Minnesota. The geometry of valleys formed by subglacial melt water may be substantially different from that formed by proglacial or preglacial streams. Subglacial streams can flow in response to hydrostatic pressure differences beneath the glacier. The valleys they erode do not necessarily have a graded longitudinal profile.

The depth of the valley cut into the St. Peter Sandstone east of the site (pl. 2) is based on two data points, well W122 drilled for this study, and well W111, reported by Schwartz (1936). The latter well has been located in the field, but an obstruction in the well bore prevents complete geophysical logging to confirm the stratigraphy.

The northernmost extent of the eastern valley (pl. 2) is based on four test wells, driller's and (or) geophysical logs of seven other wells, and a seismic refraction survey. The Platteville Limestone in this area is deeply weathered. Inspection of the Platteville Limestone by downhole television camera in test well W101 shows weathered blocks of limestone that may indicate the edge of a valley wall. The proximity of a valley is also suggested by the low water level in the Platteville Limestone at this point (pl. 3), which could be caused by flow out of the Platteville if the Glenwood confining bed has been removed by erosion. Additional field data will be obtained to determine whether a narrow valley crosses the line of section B-B' (pl. 3) between the data points, or whether the valley lies wholly south of the section.

The location of the western valley cut into the St. Peter Sandstone near the site shown in plate 2 is based on soil borings, records of three wells in the vicinity of Oxford and Louisiana Avenues, and a seismic refraction survey along the north side of Oxford Sreet. Peat with a low seismic velocity underlies the area thus complicating the interpretation of the seismic data. No well or test boring clearly indicates the presence of a deep bedrock valley in this area; therefore, the valley may be much shallower than shown or absent. In-situ weathering or subglacial erosion, rather than stream erosion, may have caused the relief on the bedrock surface.

Glacial Geology

The purpose of subsurface geologic mapping of the drift is to define areal extent and thickness of individual drift units and variations in their hydrogeologic characteristics. Test drilling by cable-tool, rotary, power-auger, and split-spoon coring methods will better define the glacial stratigraphy, particularly in the vicinity of the drift-filled bedrock valleys. Seismic refraction has been tried in an attempt to interpolate between drill holes. The particle-size distribution and mineralogy of clay and selected sand-sized fractions of the drift will be determined to aid correlation between drift units.

Porosity and vertical hydraulic conductivity of selected samples is being measured in the laboratory to estimate reasonable ranges for these characteristics. Neutron and gamma-gamma logging of selected wells, in conjunction with laboratory measurements, are being used to assess variations in effective porosity. Pumping tests will provide local values for vertical and horizontal hydraulic conductivity, storage coefficient, and specific yield, but extrapolation of these values to other locations must be based on the interpretation of the stratigraphy provided by test drilling and on laboratory measurements.

Status of Water-level Measurements and Methods Used

Water levels are being measured at about 265 wells, piezometers, and surface-water gages. The exact number of measuring sites changes continually as wells are installed, located, sealed, or reconstructed. The sites are organized by aquifer and frequency of measurement (table 2). Water levels at about 65 sites are measured at approximately 2-week intervals or by continuous or digital water-level recorders. These data were used to construct the detailed description of the ground-water flow system in the area of high concentration of contamination in the drift and Platteville aquifer (pls. 3, 4, and 5). Note that the number of wells shown in table 2 may be greater than the number of values reported on potentiometric surface maps of a particular aquifer. Not all wells in the network are accessible or suitable at every measurement date. In addition, some wells in table 2 are outside the area of the maps shown.

Table 2.--Summary of water-level measurement network as of June 30, 1979, St. Louis Park area, Minnesota

Sites measured at twice-monthly or greater frequency

Hydrologic feature	Number of sites
Lake or stream	6 (Including recorder on Minnehaha Creek maintained by Watershed District)
Drift, other than water table	18
Platteville aquifer	10
St. Peter aquifer	5 (1 recorder)
Prairie du Chien-Jordan aquifer	2 (1 recorder)
Multiaquifer wells	4 (1 recorder)

Hydrologic feature	Number of sites
Lake or stream	3
Water table	72
Platteville aquifer	30
St. Peter aquifer	25
Prairie du Chien-Jordan aquifer	51
Ironton-Galesville aquifer	0
Mount Simon-Hinckley aquifer	11
Multiaquifer wells	8

About 200 wells and surface-water gages are measured twice annually to evaluate the regional configuration of the water table and response of bedrock aquifers to pumping. Because water levels in the bedrock aquifers fluctuate rapidly, an attempt is made to measure all wells in a particular aquifer in a short time. The term "mass measurement" is used to describe this approach to collection of water-level data.

Determination of the water-level altitude in an aquifer results from two separate measurements: depth to water from a fixed measuring point and determination of the altitude above National Geodetic Vertical Datum of 1929 of the measuring point. Errors in measurement of the water level below the measuring point are small, generally less than 0.02 foot, and are seldom of significance. Errors in determination of the measuring-point altitude, however, may be substantial, depending on the method used. Because some estimates of measuring-point altitudes may be refined as part of the ongoing study, data on water-level altitudes in this report may differ from those in future reports.

Three general approaches have been used in this study. First, the measuring points of about 65 frequently measured sites near the site have been spirit-leveled from a consistent datum and water-level altitudes generally reported to the nearest 0.01 foot. The datum is derived from U.S. Geological Survey, Minnesota Department of Transportation, and U.S. Coast and Geodetic Survey bench marks. About 50 temporary benchmarks have been established. Each well in this network is tied in with closed loops. Closure errors in individual loops are typically less than 0.003 foot. The altitudes of the measuring points of clusters of wells and piezometers used to determine vertical head differences within and between aquifers are likely within this tolerance. Between widely separated wells, errors may accumulate to as much as 0.1 foot.

Barring computational mistakes, errors in this network are generally insignificant. One exception is possible change in measuring-point altitude owing to land subsidence. In particular, the measuring-point altitude of well W13 reported by Barr (1977) is 0.6 foot higher than that measured by the U.S. Geological Survey on September 15, 1978. This well is in the wetland south of the site and yields the most highly contaminated fluid of any well sampled for this study. One explanation of the differences in the measuring-point altitudes is that peat underlying the pond has compacted. This explanation is consistent with the observed lowering of the water table after the installation of storm sewers and cessation of plant process-water discharge. Dewatering from possible future remedial actions may cause further subsidence.

Second, many measuring-point altitudes have been determined by spirit-leveling from vertical-control reference marks obtained from municipalities. Water-level altitudes in this network are generally reported to the nearest 0.1 foot. Most altitudes so derived are likely accurate to at least within 0.5 foot. Altitudes of all water-table piezometers not part of the consistent vertical-control network have been determined in this way, as have altitudes of several industrial and municipal wells in the mass-measurement network.

Finally, measuring-point altitudes have been estimated from U.S. Geological Survey topographic quadrangles with 10-foot contour intervals. At best, these estimates are accurate to within several feet. Most measuring-point altitudes for wells outside of St. Louis Park in the mass-measurement network have been determined in this way. As time permits and where needed, these altitudes are being refined by spirit-leveling. Water-level information is being entered into the U.S. Geological Survey ground-water site inventory (GWSI) data base.

Bedrock Aquifer System

Water Use

Information on ground-water withdrawals was obtained from municipalities, the Minnesota Department of Natural Resources, and files of the U.S. Geological Survey. Table 3 summarizes these data by aquifer and location. Monthly pumpage records have been compiled for all municipal wells in the area. Industrial pumpage in St. Louis Park is metered by the city, and data are nearly complete for recent years. Data on industrial withdrawals in other municipalities are based on reports to the Department of Natural Resources and are less complete and less accurate than those in St. Louis Park.

Information on ground-water withdrawals is being entered in the Minnesota Department of Natural Resources water-use data base and will be stored on the University of Minnesota Computer.

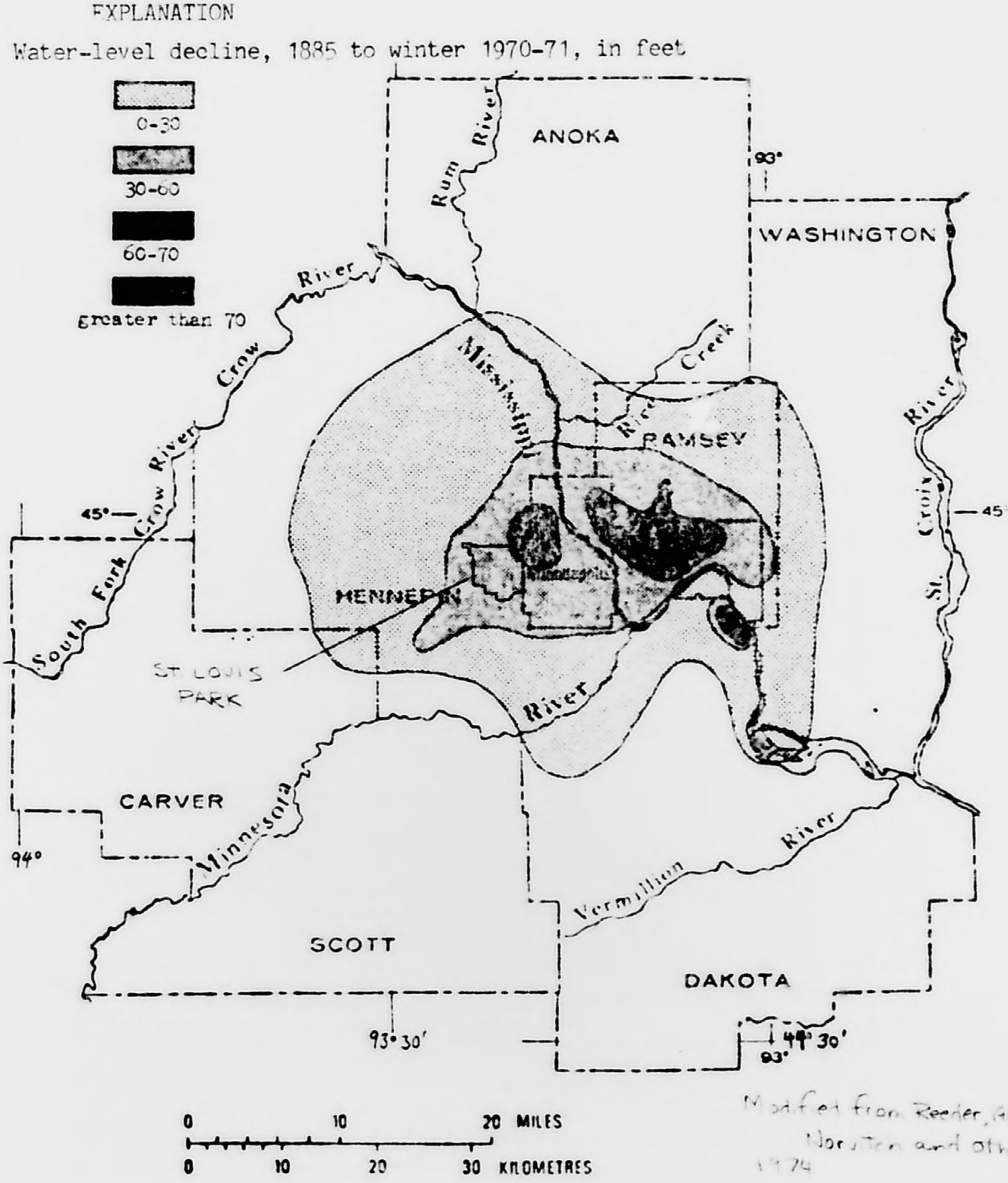
Withdrawal data from multiaquifer wells do not reflect interaquifer flow through the well bore. The rate of flow into the Prairie du Chien-Jordan aquifer owing to head differences between aquifers was estimated through the use of a down-hole current meter and exceeds the rate of pumping of the aquifer in at least one well (Wolfe Lake well, W69). Flow out of the St. Peter and Platteville aquifers into underlying bedrock aquifers through multiaquifer wells likely exceeds the amount of water withdrawn from the St. Peter and Platteville aquifers by pumping.

Approximately 75 percent of withdrawals are from the Prairie du Chien-Jordan aquifer. Most other withdrawals are from the Mount Simon-Hinckley aquifer. Only one high-capacity well, SLP3, is known to be in use and to yield water principally from the St. Peter aquifer. This well is also completed in the Platteville aquifer and may affect the potentiometric surface of that aquifer. No other high-capacity wells are known to obtain supplies from the drift or Platteville aquifers.

Prairie du Chien-Jordan Aquifer

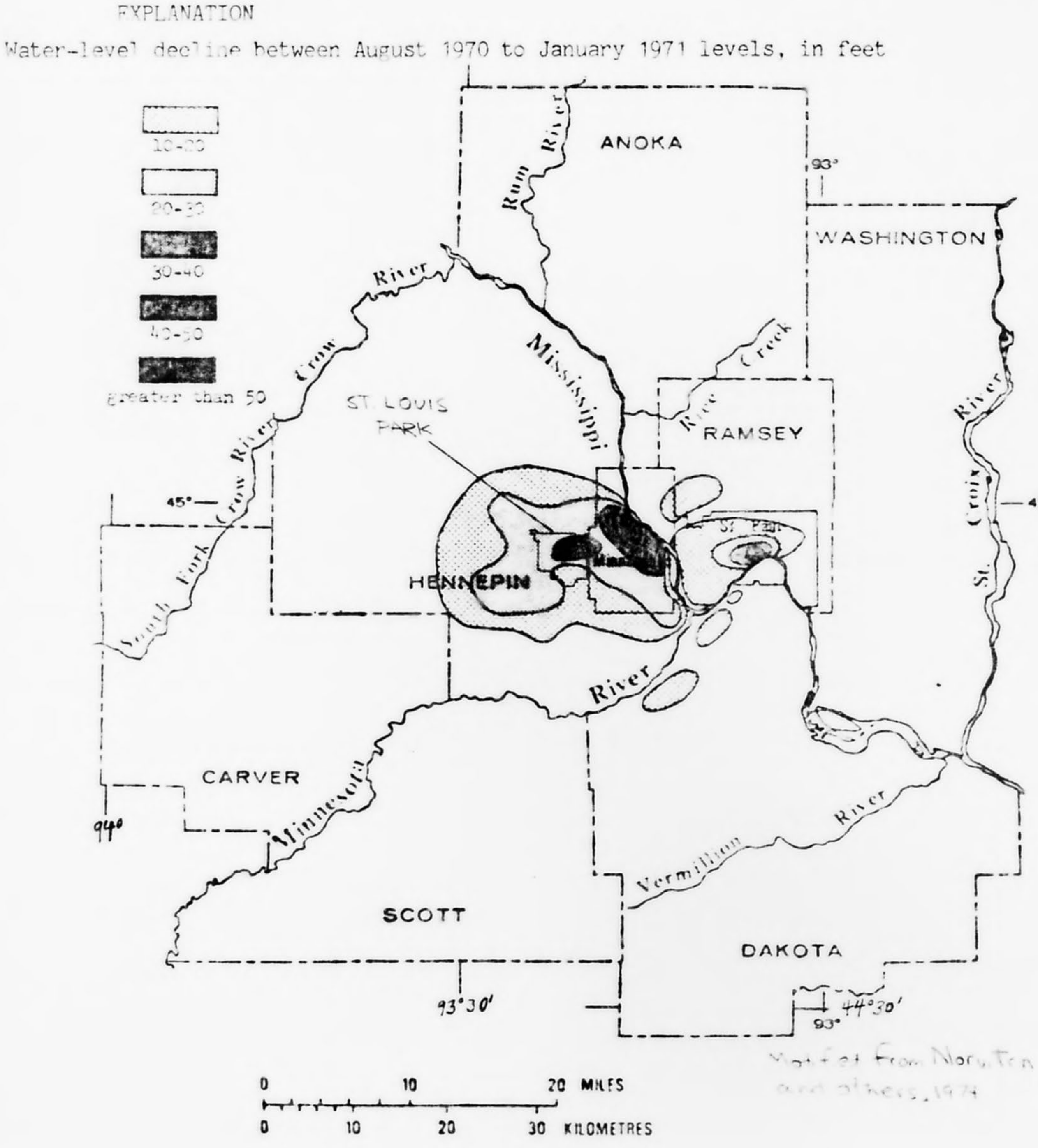
Withdrawals from the Prairie du Chien-Jordan aquifer have created a long-term potentiometric surface change (fig. 6). The regional hydraulic gradient is now generally to the east. Increased pumpage during the summer causes short-term, regional declines (fig. 7). Changes in water level at any individual well reflect both regional and nearby conditions. Figure 8 shows the relationship between the static water level in Old SLP1 and pumpage from adjacent wells. The hydrograph of Old SLP1 shows the regional seasonal fluctuations (fig. 8). Continuous records (1953-76) and measurements at 30-minute intervals (1977-79) indicate a cyclical weekly fluctuation of about 2 feet in addition to the seasonal fluctuations.

The combination of the regional hydrologic gradient and the effects of pumping and multiaquifer wells create a complex potentiometric surface. Figures 9, 10, and 11 show the generalized potentiometric surface of the aquifer on January 30-31 and June 20-23, 1979, and the change in water level between



Modified from Reeder, 1965; Norvitch and others, 1974

Figure 6.--Long-term potentiometric surface change in the Prairie du Chien-Jordan aquifer caused by ground-water withdrawal, 1885 to winter 1970-71



Modified from Norvitch and others, 1974

Figure 7.--Short-term seasonal potentiometric surface decline in the Prairie du Chien-Jordan aquifer caused by ground-water withdrawal, winter 1970-71 to August 1971

Table 3.--Summary of ground-water use in the St. Louis Park area, Minnesota

Site identification (latitude and longitude)	Aquifer(s)	Well name and(or) number	Date of instal-lation	Period of monthly pumpage records	Pump capacity (gal/min)	1976 Total reported pumpage, summary (gallons)
		INDUSTRIAL WELLS				
445615093212301	Prairie du Chien-Jordan	Minnesota Rubber (W40)	8/50	1968-78	300	81,778,840
445604093223801	Prairie du Chien	Flame Industries (W29)	4/63	1968-78	100	11,923,868
445618093210001	St. Peter-Prairie du Chien	S & K Products 1(W45)	7/63	1968-78	175	Not in use
445617093210201		2(W46)	2/73	1973-78	175	6,582,000
445646093214601	Prairie du Chien-Jordan	Methodist Hospital	1958	1973-78	---	228,170,300
445721093221801	St. Peter-Prairie du Chien	McCourtney Plastics (W62)	9/66	1975-78	250	59,976,131
445733093214301	Prairie du Chien	Food Producer	---	1969-78	---	66,281,040
445608093240301	Prairie du Chien-Jordan	Red Owl	10/46	1973-78	---	81,752,286
		ST. LOUIS PARK MUNICIPAL WELLS				
445701093215803	Platteville-St. Peter	3	8/39	1947-48, 1961-64, 1975-78	1,200	125,878,400
445548093202201	Prairie du Chien-Jordan	4	9/46	1948-64, 1975-78	1,000	91,747,970
445631093230301	do	5	8/47	1948-64, 1975-78	1,200	151,458,650
445626093211401	do	6	1/48	1948-64, 1975-78	1,200	349,558,260
445727093221701	do	7	5/52	1953-64, 1975-78	1,200	21,806,970
445806093241101	Jordan	8	10/55	1956-64, 1975-78	1,200	375,317,050
445730093222601	Prairie du Chien-Jordan	9	1955	1960-64, 1976-78	1,200	21,807,170
445701093215804	do	10	1955	1956-64, 1975-78	1,200	86,162,850
445701093215805	Mount Simon-Hinckley	11	11/60	1961-78	1,200	315,796,700
445526093211402	do	12	8/63	1964-78	1,400	108,437,660
445756093211701	Hinckley	13	7/64	1965-78	1,400	101,826,750
445756093211702	Jordan	14	2/65	1965-78	1,200	102,363,770
445701093215806	do	15	1969	1970-78	1,200	232,574,200
445750093234801	do	16	7/73	1974-78	1,200	442,279,000
445614093204101	Prairie du Chien	Wolfe Lake (W69) (Hedberg-Friedheim)	7/47	1970-79	---	None

Table 3.--Summary of ground-water use in the St. Louis Park area, Minnesota--Continued

Site identification (latitude and longitude)	Aquifer(s)	Well name and(or) number	Date of instal- lation	Period of monthly pumpage records	Pump capacity (gal/min)	1976 Total reported pumpage, summary (gallons)
445730093193801	St. Peter-Prairie du Chien	Twin Lakes	5/60	---	---	None
EDINA MUNICIPAL WELLS						
445442093202601	Jordan	2	1935	1958-64, 1969-77	900	426,534,700
445430093194701	Prairie du Chien-Jordan	3	1947	do	800	39,110,800
445356093203801	do	4	1950	do	700	167,694,300
445245093194001	do	5	5/54	do	1,000	86,845,700
445345093204801	do	6	6/54	do	1,000	348,150,000
445355093212201	Prairie du Chien-Jordan	7	1955	do	1,000	72,571,400
445301093213701	Jordan	8	1953	do	1,000	64,247,200
445349093222501	Mount Simon-Hinckley	9	1957	do	1,000	74,014,800
445153093195801	do	10	9/63	1964, 1969-77	1,000	256,503,900
445153093195802	Jordan	11	1963	do	1,000	397,258,000
445513093231201	Hinckley	12	9/64	do	1,000	57,581,000
445513093231202	Jordan	13	9/64	do	1,000	385,594,000
445202093230201	Prairie du Chien-Jordan	14	1964	do	1,000	46,417,800
445443093222901	Prairie du Chien	15	11/67	1969-77	1,000	169,428,000
445317093225801	Prairie du Chien-Jordan	16	11/67	do	1,000	306,421,000
445345093200801	Jordan	17	1970	1971-77	1,000	117,494,200
445206093191401	do	18	1973	1974-77	1,000	49,789,000
HOPKINS MUNICIPAL WELLS						
445514093244301	Prairie du Chien-Jordan	1	1920	1958-78	850	268,984,400
445550093230801	do	3	1948	1958-78	1,250	71,314,500
445607093250501	do	4	5/54	1958-78	2,300	573,860,000
445607093243701	do	5	1967	1967-78	2,050	(Wells 4 & 5 combined)
445559093243501	do	6	1977	1977-78	2,200	None

these two periods. Small vertical differences in head have been measured within the Prairie du Chien-Jordan aquifer at one location (Reeder and others, 1976). These differences, residual drawdown, and the effects of nearby multi-aquifer and withdrawal wells account for some of the observed local variation in head between closely spaced wells in the Prairie du Chien-Jordan aquifer.

The regional hydraulic gradient shown in figures 9 and 10 generally agrees with maps compiled by Norvitch and others (1974), Reeder (1966), and Liesch (1961) from fewer water-level measurements made over a longer period of time. The eastward flow direction is supported by water-quality interpretations (Maderak, 1964; 1965). Dissolved solids increase as water moves eastward from the major recharge area near Lake Minnetonka.

Mount Simon-Hinckley Aquifer

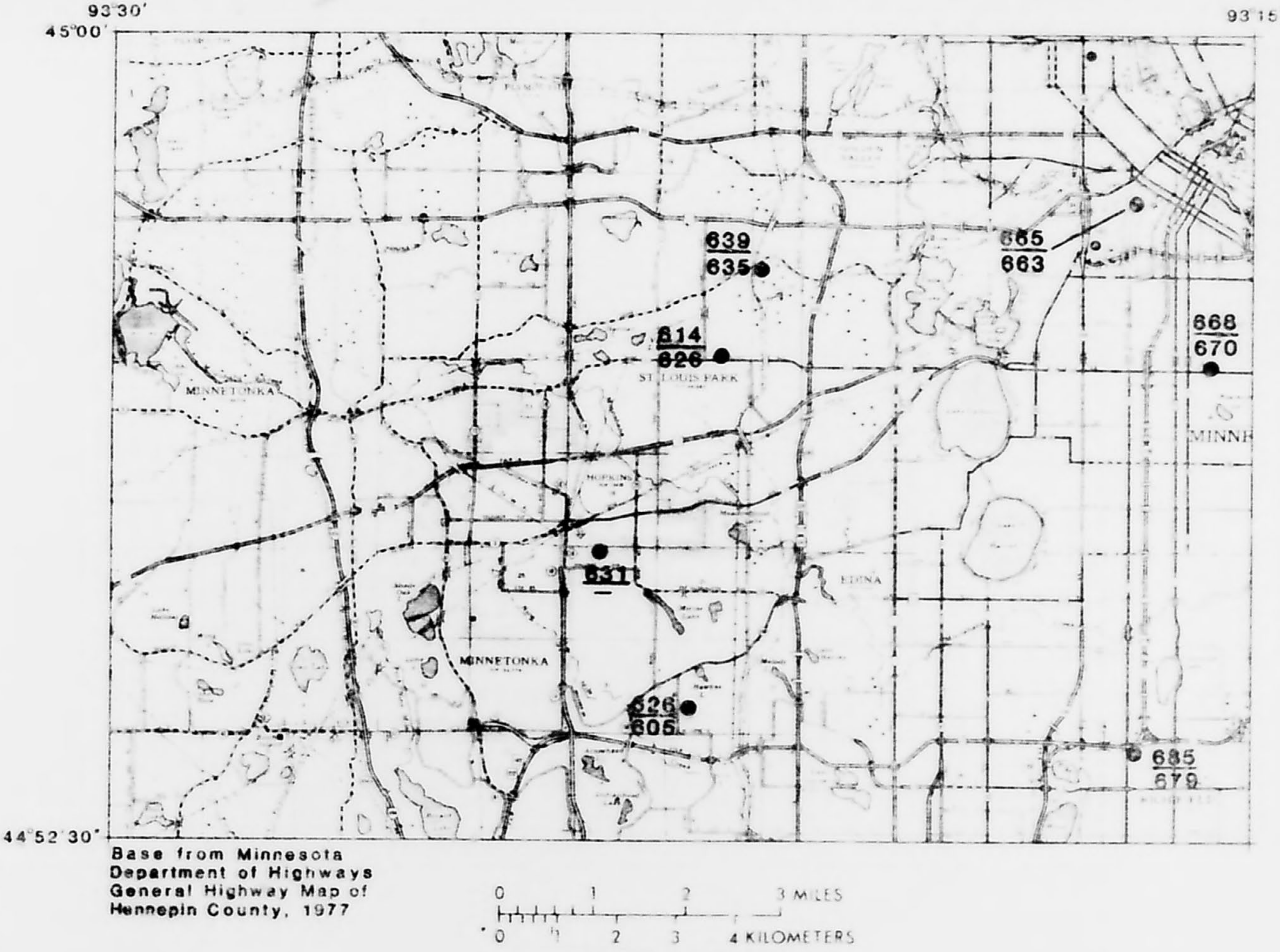
The Mount Simon-Hinckley aquifer provides approximately 15 percent of the ground water withdrawn in the area. However, few wells are available for measurement of water levels because the aquifer is deeply buried, and only a few wells are open to the aquifer. Most water-level measurements were made in high-capacity municipal and industrial wells and the measurements may be affected by residual drawdown. Results of water-level measurements are shown in figure 12. Pumping by municipal wells in St. Louis Park and Edina has affected water levels locally. It is not known, however, whether local drawdown effects from individual wells have coalesced to form one or more large, closed depressions in the regional potentiometric surface. It is possible that water in the Mount Simon-Hinckley aquifer moves toward the municipalities from all directions.

Multiaquifer Wells

A major effort has been made to locate and evaluate multiaquifer wells. Data on wells were initially obtained from the files of the U.S. Geological Survey, the Minnesota Geological Survey, the St. Louis Park Department of Public Works, and previous reports (principally: Fuller, 1904; Hall and others, 1911; Schwartz, 1936; Minnesota Department of Health, 1938; Hickok, 1969; Olson and others, 1974; Sunde, 1974; Barr, 1977). Additional information was obtained from discussions with area residents, employees of local businesses, and drillers. Greatest priority was given to a 2-square-mile area surrounding the site in which attempts are being made to locate and test all wells.

Data on some of these wells are presented in table 1 and (or) have been entered in the U.S. Geological Survey GWSI data base. As wells are located in the field, logged geophysically, reconstructed, or permanently abandoned, information on them is updated.

Approximately 30 uncased or ungrouted bedrock wells have been logged with a downhole television camera by the Minnesota Department of Health and (or) geophysically logged by the U.S. Geological Survey. Where possible, water levels and depths of wells were measured and the wells were geophysically logged to verify well construction and stratigraphy and to measure vertical flow. These geophysical logs, driller's logs, water-level measurements, and leveling results are available for inspection at the U.S. Geological Survey, St. Paul, Minn.



Base from Minnesota
Department of Highways
General Highway Map of
Hennepin County, 1977

EXPLANATION

● 626/605 Location of well,
Upper number denotes water level measured January 30-31, 19
Lower number denotes water level measured June 20-22, 1979
above National Geodetic Vertical Datum of 1929

Figure 12.--Water levels in the Mount Simon-Hinckley aquifer, January 30-31 and June 20-23, 1979

A multiaquifer well can provide an avenue for the transport of contaminants and locally change the potentiometric surfaces of the aquifers that are connected. Water moves from one aquifer to another through multiaquifer wells in response to differences in water levels between aquifers. In the study area, the water level in each aquifer is higher than in underlying aquifers and flow through multiaquifer wells, therefore, is downwards.

As used in this report, a multiaquifer well is any well that hydraulically connects more than one aquifer (see glossary). The interconnection may be due to one or more of the following factors: (1) Original open-hole construction, (2) leaks in the casing, or (3) flow in the annular space between the casing and the bore hole. Detecting and measuring flow in the annular space outside casings generally requires specialized techniques that are beyond the scope of this study. References to flow through multiaquifer wells in this report are to flow inside the casing or in an uncased part of the well bore.

Uncased or ungrouted wells that penetrate more than one aquifer provide avenues for the transport of contaminants. The effect of an individual well depends on (1) the rate of flow down the well bore, (2) local and regional ground-water flow patterns, and (3) contaminant concentration. The rate of flow down the well bore depends primarily on the thickness and hydraulic conductivity of the aquifers, the head differences between them, and well construction and condition. For a given well of known original construction, the most difficult factor to estimate is present well condition because multiaquifer wells tend to be unstable, and casings deteriorate with time. A phenomenon known as "skin effect" occurs when the pores of the aquifer into which water flows are clogged by sediment, biologic films, or chemical encrustation.

Well W23 ("Hinckley" well on the site; table 1, fig. 3, and pl. 1) is a multiaquifer well that is particularly important because the well bore is partly filled with coal-tar. When drilled in 1917, the well was 909 feet deep and may have permitted the flow of water out of the Prairie du Chien-Jordan aquifer and into the underlying Ironton-Galesville and Mount Simon-Hinckley aquifers. By early 1977, however, water was moving into the Prairie du Chien-Jordan aquifer from the overlying St. Peter aquifer. A downhole television camera survey and geophysical logging in 1978 showed that the well was 595 feet deep, visibly contaminated, and that water was entering the well bore through holes in the casing adjacent to the St. Peter Sandstone (fig. 13). About 150 gal/min of water was leaking into the well bore, flowing downward, and entering the Prairie du Chien through another hole in the casing.

The estimate of flow was made from independent measurements through use of the television camera and an impeller-type velocity probe that was approximately calibrated in the hole. Methods of flow measurement in well bores are discussed by Patten and Bennett (1962).

Periodic water-level measurements and a second television survey confirmed that the flow was sustained. In July 1979, the city of St. Louis Park had a temporary packer installed in the well to stop the flow. The well was equipped in 1979 with digital recorders to obtain water levels above the packer (St. Peter aquifer) and below the packer (Prairie du Chien-Jordan aquifer and St. Lawrence-Franconia confining bed).

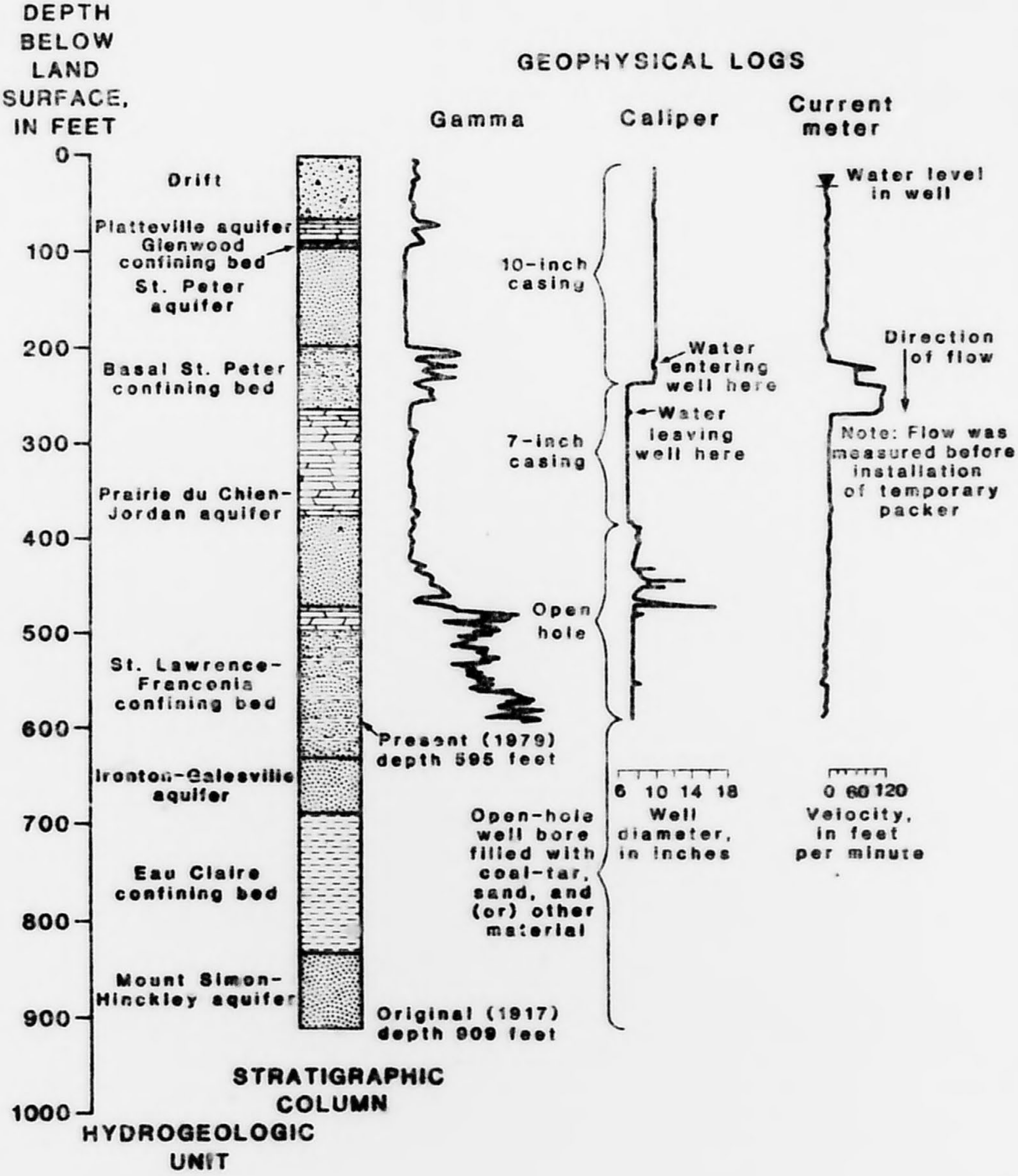


Figure 13.--Geologic and geophysical logs of well W23 ("Hinckley" well on the site)

A multiaquifer well changes the direction of ground-water flow in the vicinity of the well. A cone of depression is created in the aquifer of higher head by withdrawal of water from it; conversely, a cone of impression is created in the aquifer of lower head by the flow of water into it (fig. 14). The shape and area of influence of these cones depends on the rate of flow, aquifer characteristics, head differences, stresses, such as pumping wells and flow through other multiaquifer wells, and hydrogeologic boundaries, such as drift-filled bedrock valleys. For instance, figure 15 indicates a gradient in the St. Peter aquifer toward well W23. This may be due both to a cone of depression in this aquifer caused by flow out of the aquifer through the well and increased recharge to the St. Peter aquifer from the drift-filled valley near well W24.

The water level in a multiaquifer well reflects the cone of impression or depression in each aquifer to which it is hydraulically connected. If well loss, skin effects, and head differences needed for flow to occur within the well bore are negligible, the water-level altitude in a multiaquifer well is equal to the potentiometric head in each aquifer to which it is open.

A cone of impression caused at least in part by well W23 was formed in the Prairie du Chien-Jordan aquifer at the site. Static water levels measured by the U.S. Geological Survey on August 23, 1977, at five St. Louis Park municipal wells (SLP5, SLP8, SLP9, SLP10, and Old SLP1) completed in the Prairie du Chien-Jordan aquifer are shown in plate 1. The water level in well W23 is higher than the water levels measured in surrounding wells constructed in the Prairie du Chien-Jordan aquifer, therefore it indicated that a cone of impression had been created by water moving through the well bore of well W23 from the overlying St. Peter aquifer. The water level in well W23 shown on plate 1 was not measured in August 1977, but an estimate was made for this date from 18 measurements since April 1978 and a water level in the spring of 1977 inferred from Barr (1977, p. III-34).

The data indicate that on August 23, 1977, water in the Prairie du Chien-Jordan aquifer was moving away from W23 in all directions but that the hydraulic gradient was steepest between W23 and the municipal well field to the north. The gradient to the north has decreased since this time in apparent response to the interruption in use of four municipal wells in the Prairie du Chien-Jordan aquifer (figs. 9, 10, and pl. 1). These wells were found to be contaminated in 1978 (Minnesota Department of Health, 1978).

Four other wells have been located that were causing water to flow into the Prairie du Chien-Jordan aquifer from overlying aquifers (Wolfe Lake Well, W69; Hedberg-Friedhiem, W114; Burdick Grain, W47; Prestolite, W50). These wells were sampled by the Minnesota Department of Health. Each has been permanently sealed with grout. Water pumped from wells W114 and W50 had a distinct chemical odor at the time of sampling. Chemical analysis of water pumped from well W47 did not indicate significant quantities of contaminants.

The permeability of the upper part ot the Prairie du Chien-Jordan aquifer (Prairie du Chien Group) is due to solution channels and open joints (pl. 2; geologic and water-bearing characteristics of hydrogeologic units). These openings are large compared to the intergranular pores of sandstone and are less

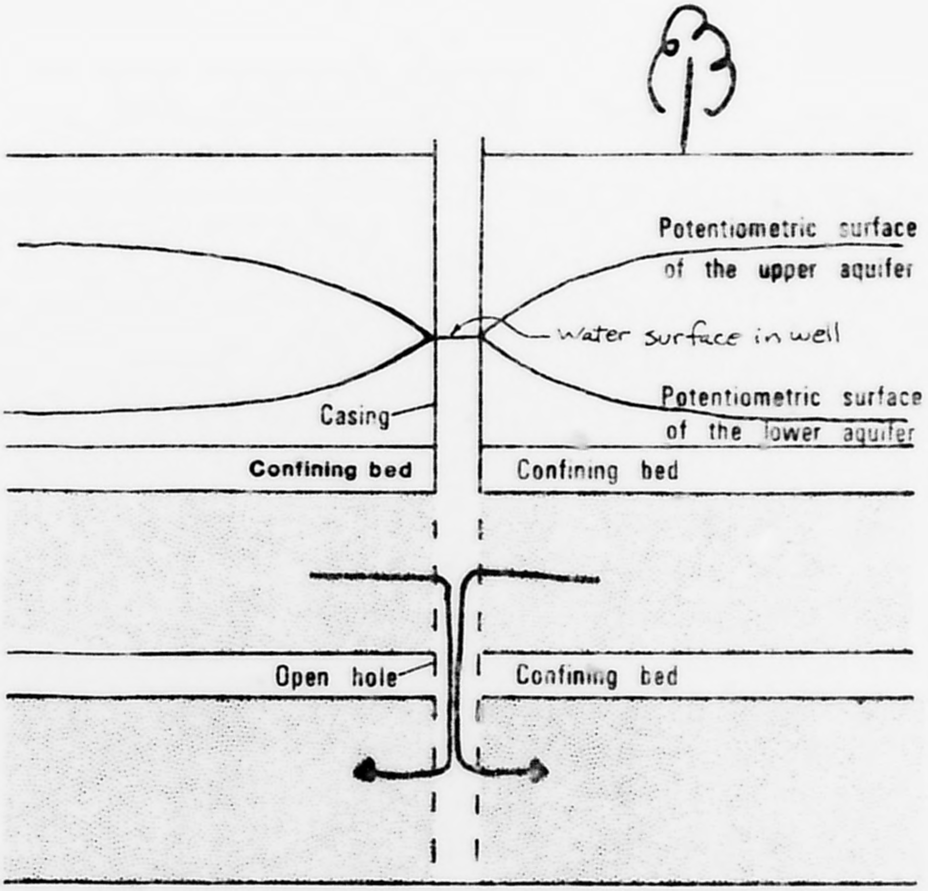


Figure 14.--Schematic hydrologic section showing a well connecting two confined aquifers, flow through the well bore, and the effects of this flow on the potentiometric surfaces of the two aquifers

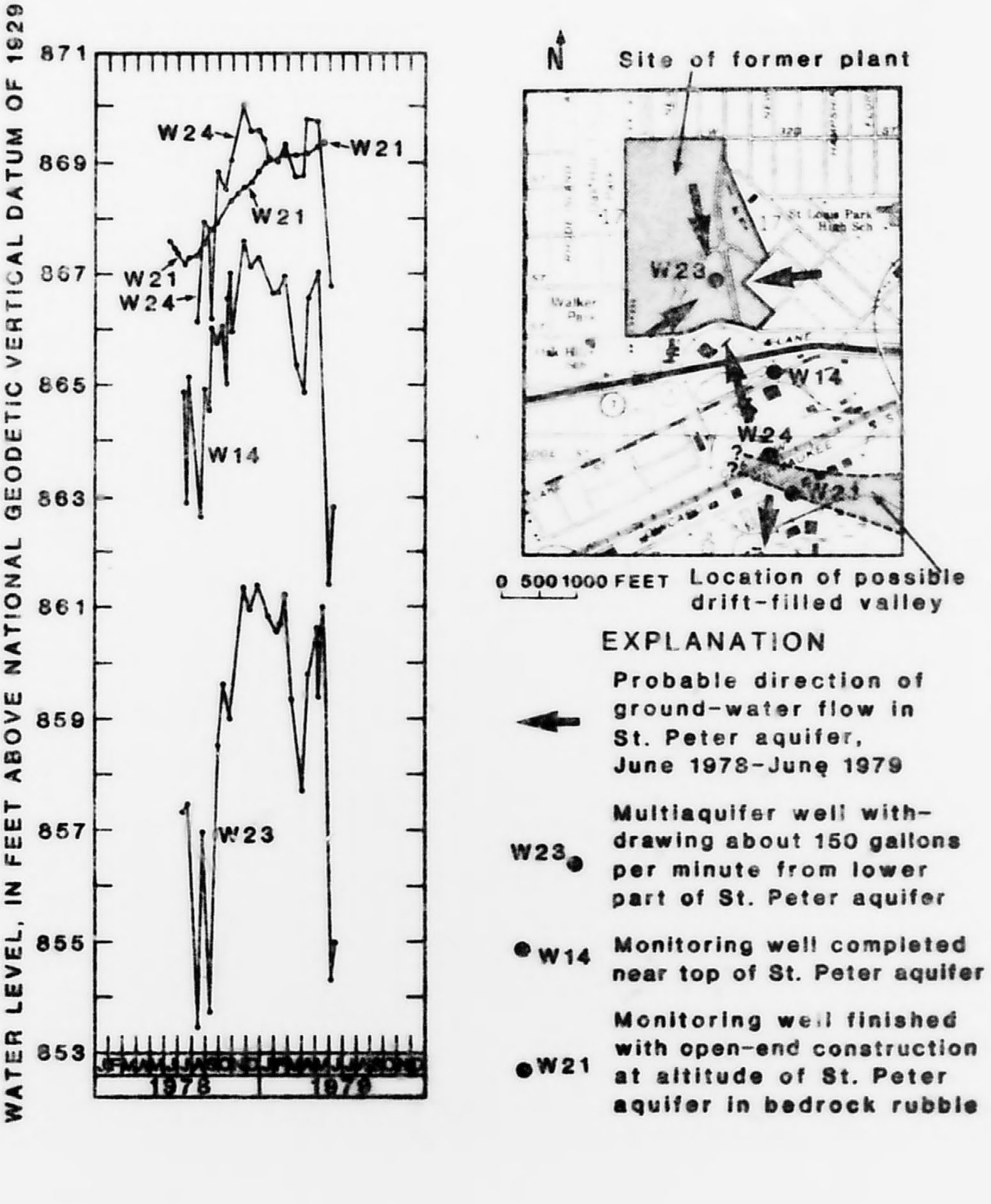


Figure 15.--Relationship between water levels in multiaquifer well W23 and wells W24 and W14 in the St. Peter aquifer

susceptible to clogging with sediment and to other skin effects. The ability of the Prairie du Chien Group to accept large quantities of sediment entrained in the downward flow was observed in well W69. With downhole television, sand from the St. Peter aquifer could be seen entering through a hole in the casing, flowing downward with the water, and moving out of the well bore through a solution channel at the bottom of the well. The well had been filled, apparently with sand from the St. Peter aquifer, to the level of the solution channel.

The head difference between the Platteville and St. Peter aquifers is generally about 20 feet. No flow was detected from the Platteville into the St. Peter aquifer in uncased wells that were geophysically logged or evaluated by downhole television camera. The lack of measureable flow is attributed to skin effects. In general, unused Platteville-St. Peter multiaquifer wells do not significantly change the potentiometric surfaces of the Platteville and St. Peter aquifers. However, the open well bore between the Platteville and St. Peter aquifers may provide a pathway for significant transport of contaminants. For instance, a dilution of contaminated water from the Platteville in the vicinity of well W33 (Strand Manufacturing) by a factor of 1,000 will still produce detectably contaminated water in the St. Peter aquifer. Reconstruction of well W33 was completed on July 5, 1979, by the Minnesota Department of Health to prevent such leakage. More observation wells will be needed to clearly evaluate whether or not Platteville-St. Peter multiaquifer wells have had a measurable effect on the quality of water in the St. Peter aquifer.

Drift-Platteville Aquifer System

The upper surface of the ground-water system is the water table. The generalized configuration of the water table is shown in figure 16. The water table ranges from an altitude of 900 feet near Minnehaha Creek west of the site to 850 feet at Lake Calhoun to the east. This map (fig. 16) is in general agreement with regional maps prepared by Larson-Higdem and others (1975).

As far as is known, naturally occurring surface-water bodies in the area are surface expressions of the water table. They may also form hydrogeologic boundaries in the drift-Platteville aquifer system by controlling the altitude of the water table. The quantity of ground water entering or leaving a stream sometimes can be estimated by measuring stream discharge. Low-flow discharge measurements on November 3, 1978, at four locations on Minnehaha Creek between Cambridge Street and Louisiana Avenue indicated discharges of 10.9, 11.7, 14.1, and 12.8 ft^3/s. Although channels are well defined at these sites, some of the observed differences may be due to measurement error rather than net gains or losses of the stream. Additional analysis of data collected to date is needed to evaluate the extent to which surface-water bodies are hydrogeologic boundaries.

The detailed stratigraphy of the drift is complex, but three areally persistent units of hydrogeologic significance have been identified (Barr, 1976; 1977) (1) the Middle Drift aquifer of glacial sand and gravel, (2) an overlying confining bed of lake deposits and till, and (3) the underlying basal drift complex of till, outwash, valley-fill deposits, and deeply weathered bedrock. A fourth unit, the Upper Drift aquifer, is poorly defined and is not continuous in the study area. These units are shown schematically in sections A-A' and B-B' (pl. 3).

The geometry of the Middle Drift aquifer is irregular, but its hydraulic continuity has been tentatively established by test drilling and measurements of areal and vertical variations in head (pl. 4). Measurements at piezometer clusters show that vertical differences in head within the aquifer are generally less than 0.03 foot (pl. 3), indicating that the flow of water is primarily horizontal. The potentiometric surface of the aquifer generally slopes to the east (pl. 4).

The contacts between the Middle Drift aquifer and the overlying confining bed and the underlying basal drift complex are indistinct in places. For example, observation well W10 has been previously identified as being completed in the Middle Drift aquifer (Barr, 1976; 1977). It is so identified on plates 4 and 6. However, based on logs of additional wells installed at the same location, the Middle Drift aquifer is either very silty or absent. On the generalized hydrogeologic section A-A' (pl. 3), the well is shown to be completed in the upper confining bed because there seem to be significant changes of head with depth within this interval of drift.

The aquifer is vertically recharged through the upper confining bed from infiltration of precipitation and leakage from the Upper Drift aquifer, where present. Evaluation of water-level measurements suggests that, during the recharge period of spring 1979, a major part of the recharge entered the area from the west and north, with recharge being significant and rapid locally at and south of the site. The local recharge resulted in minor, short-term reversals in flow direction, as indicated by the intersection of the hydrographs for wells W2 and W5 (pl. 4).

In the spring of 1979, this local recharge occurred in the area that previously received plant-process water and surface-water runoff from the site. The direction of ground-water flow and contaminant transport may have changed since the plant was in operation (1918-72) owing to changes in the distribution of recharge. Surface water is now (1979) discharged to Minnehaha Creek through storm sewers.

Water from the aquifer discharges laterally to the east and southeast and vertically into the basal drift complex. Sporadic dewatering of the drift at a construction site near Louisiana Avenue and Oxford Street has locally affected water levels, but the rate and timing of pumpage is poorly known. No other current water withdrawals from the drift have been identified.

Because vertical head varies appreciably with depth in the basal drift complex, meaningful areal maps of water-level altitudes in this unit cannot be drawn. However, measurements of water levels in the unit can be used to construct isopotential lines to describe the vertical and horizontal direction of flow, as shown in the hydrogeologic sections (pl. 3). Head differences between the top and bottom of the basal drift complex indicate that vertical leakage out of the Middle Drift aquifer through the lower drift complex and into the Platteville aquifer or valley fill may be appreciably greater in the vicinity of the buried valleys. Winter and Pfannkuch (1976) discuss the hydrogeologic significance of drift-filled bedrock valleys in the Minneapolis-St. Paul Metropolitan area. They suggest many of these valleys may be filled with coarse-grained deposits and may provide preferential pathways for movement of contaminants.

The Platteville aquifer is a nearly flat-lying limestone underlain by the Glenwood confining bed. Water-level altitudes in Platteville observation wells are shown on plate 5. The water levels are not contoured because the effects on the potentiometric surface of buried bedrock valleys, multiaquifer wells, and possible vertical head differences within the aquifer are not yet sufficiently well known. The regional gradient of the potentiometric surface of the Platteville aquifer, however, is similar to that of the Middle Drift aquifer and to the configuration of the water table.

Contours of the potentiometric surface locally may parallel bedrock valleys, where the Platteville and Glenwood have been removed by erosion, and water may move laterally out of the Platteville and into the valley-fill deposits contained in these bedrock valleys. This is the tentative interpretation presented on the hydrologic sections shown in plate 3. The vertical head difference between the Middle Drift and Platteville aquifers ranges from less than 0.1 foot at the observation wells farthest from the buried valleys (W2, W100) to more than 10 feet near the possible valley at the intersection of 36th Street and Wooddale Avenue (W117, P18, W101).

The hydraulic characteristics of solution-channel carbonate rocks, such as the Platteville aquifer, may differ widely from place to place. Liesch (1973) has documented large local differences in the transmissivity and storage coefficient of the Platteville aquifer near Minnehaha Creek in Minneapolis. However, short-term pumping tests (pl. 5) indicate that the hydraulic characteristics of the Platteville aquifer, particularly transmissivity, are reasonably uniform in the St. Louis Park area. The time-drawdown curve for well W101 seems anomalous and may reflect its proximity to the drift-filled valley. Well W101 is completed in the lower part of the Platteville aquifer, and the large head differences between this and adjacent Platteville wells may indicate significant vertical gradients within the aquifer. Most of this head difference is tentatively attributed to local downward flow toward the valley (pl. 3); here, and elsewhere, withdrawal through multiaquifer wells may cause local cones of depression.

At the well cluster near Lake and Monitor Streets (W9, W14, W18, P8, P14, P15; pl. 3), the head difference between the Platteville and St. Peter aquifers is about 20 feet. This head difference causes water to flow vertically downward through the Glenwood confining bed. The water level in the Platteville aquifer at well W101 near the bedrock valley is very nearly that of the St. Peter aquifer at nearby well W111.

Of the five wells in the Platteville aquifer equipped with water-level recorders (W18, W19, W20, W22, W101), the rate and magnitude of water-level fluctuations is greatest in well W101. The hydrographs shown on plate 5 were prepared from measurements made at approximately 2-week intervals and cannot show rapid changes. The fluctuations in water-level in well W101 may be due to changes in flow rates from the Platteville into the buried valleys and through multiaquifer wells owing to variations in pumping from underlying bedrock aquifers. Preliminary digital-computer simulations indicate that the drift-Platteville aquifer system may be sensitive to such pumping stresses, depending largely on the location and effect of multiaquifer wells and the vertical hydraulic conductivity of the valley-fill material and the confining beds at the base of the St. Peter aquifer.

CHEMICAL QUALITY

Status of Data Collection and Methods Used

Organic contaminants are present in the ground-water system in three forms:

1. Aqueous phase - hydrocarbons, miscible with water, that are in a virtually dissolved form.
2. Hydrocarbon fluid phase - a liquid mixture of hydrocarbons, immiscible with water, which forms a fluid phase physically distinct from the aqueous phase.
3. Hydrocarbon solid phase - hydrocarbons sorbed onto the matrix of porous media.

The aqueous phase is the most mobile and the most easily sampled. Initial efforts focused on sampling it to evaluate the areal and vertical extent of contamination.

Fluid samples for chemical analysis were collected in March and April 1979 from 25 wells in the drift and the Platteville and St. Peter aquifers by techniques outlined by Brown and others (1970) and Wood (1976). The general procedure was as follows: the well was pumped at 10 to 15 gal/min by submersible pump and the drawdown in the well measured to evaluate well performance. Samples were taken and pH measured after the specific conductance and temperature of the water stabilized, usually within half an hour. Appropriate preservatives were added, the samples were chilled immediately, and delivered the same day to the Minnesota Department of Health for analysis. Alkalinity was determined in the field by potentiometric titration and in the laboratory. Samples for dissolved inorganic constituents were filtered in the field through a 0.45-micrometer cellulose filter in-line with the pump discharge. Samples for dissolved and suspended organic carbon (see glossary for definition) were filtered in the field by use of a 0.45-micrometer silver filter and analyzed by the U.S. Geological Survey.

Data from these analyses are presented in table 4 and have been entered into WATSTORE. Data from WATSTORE can also be obtained through STORET.

Preparation of sample bottles, sample extraction, and chemical analysis of individual organic compounds was done by the Minnesota Department of Health. Samples were collected in 1-gallon amber glass bottles that had been cleaned and oven-heated to remove possible contaminants. Separation of the organic compounds from the sample by extraction with cyclohexane was generally done the day after sampling by a method modified from Sorrell and others (1977). Ten of the extracts were analyzed in the first year of the study by high-performance liquid chromatography for polynuclear aromatic hydrocarbon (PAH) compounds. Data for these samples are shown on plate 5. WATSTORE and STORET parameter numbers have not been assigned to these constituents, and the values have not been entered into these data bases.

In addition to the fluid samples, four core samples of drift material from a boring at the site of well W9 were chemically analyzed by the U.S. Geological Survey to attempt to identify as many organic compounds as possible. Each sample was split lengthwise and the subsamples extracted and separated into acid, neutral, and basic fractions by two different methods. The extracts were analyzed by flame-ionization gas chromatography and confirmed with mass spectrometry. In neither case were contaminants detected in the acid fraction. However, pthalate compounds were found in the basic fraction.

Nearly all the organic compounds detected were in the neutral fraction. Analysis of one core indicated that naphthalene constituted 90 percent of the contaminants detected. Analysis of fluid pumped from wells by the Minnesota Department of Health using high-performance liquid chromatography did not measure the naphthalene concentration, but a larger number of individual compounds was identified than in the cores. Subsequent analysis of fluid from well W9 by the Minnesota Department of Health by gas chromatography has confirmed the high concentration of naphthalene relative to other compounds identified.

Work is continuing to identify all major compounds. To date, the sum of the measured concentration of individual constituents is generally less than 10 percent of contaminant concentrations measured as TOC (total organic carbon), DOC (dissolved organic carbon), and SOC (suspended organic carbon). Work on complete characterization of the contaminants by the U.S. Geological Survey will be continued on fluid samples rather than core samples to (1) isolate the problem of compound detection, identification, and quantitation from that of developing adequate techniques to extract contaminants from core samples; and (2) provide greater contaminant mass for analysis.

As part of the project, laboratory column experiments are being made by H. O. Pfannkuch, Department of Geology and Geophysics, University of Minnesota, to evaluate the mobility of selected organic compounds in drift materials. Separate glass columns were packed with a control media, whose physical properties are well known ("Ottawa sand"), and with drift materials. The mineralogy of the column-packing materials was determined by X-ray diffraction and point-counting. The particle-size distribution was measured and used to estimate effective grain area. The hydraulic conductivity and porosity of the column packs were determined. The columns were filled and air bubbles removed with degassed, distilled water, and sterilized. Water was circulated through the column at a known rate, a tracer injected, and the effluent concentration curve determined.

Dispersion characteristics of the columns have been determined using a conservative inorganic tracer (chloride) to assist in differentiating between hydrodynamic dispersion and sorption-desorption processes. Dispersion characteristics and tracer retention will be evaluated for napthalene and additional coal-tar derivatives. Laboratory values for dispersion are typically several orders of magnitude lower than apparent dispersivities in real hydrologic systems. However, the differences in behavior between various combinations of tracers and column-packing materials will lend insight into field sorption-desorption processes.

Chemical and Physical Behavior of Organic Contaminants

The transport of contaminants in the ground-water system is complex. Figure 17 describes a preliminary conceptual model of the overall process, including modes of introduction and interaction between the drift-Platteville aquifer system and underlying bedrock units. Figure 18 describes in greater detail possible major physical and chemical transport processes within the drift-Platteville aquifer system.

An important distinction between the transport processes of most natural constituents of ground water and the transport of coal-tar derivatives is that many compounds in coal tar are relatively insoluble (pl. 6; data from May and others, 1978; Schwarz, 1977; Sutton and Clader, 1975). If liquid hydrocarbons are introduced into the ground-water system more rapidly than they can be dissolved and removed from the point of introduction by ground-water flow, a second fluid phase composed of hydrocarbons will develop (fig. 18). Because this second phase has physical properties that differ from that of the aqueous phase, the hydrocarbons may move at a rate and direction different from the water. Coal-tar constituents typically have specific gravities greater than that of water (pl. 6) and a hydrocarbon-fluid phase will tend to move vertically downward with respect to water. Stallman (1964) and Bear (1972) present reviews of the behavior of multiphase fluids in porous media.

The surface tension and viscosity of liquid coal-tar mixtures is significantly greater than that of water. With equal head gradients, degree of saturation of the pore space, and intrinsic permeability, the velocity of a coal-tar fluid phase will be very much less than that of the aqueous phase. These effects may be the cause of the anomalous time-drawdown curves of two wells, W13 and W6, in the most heavily contaminated parts of the Middle Drift aquifer (pl. 4). One hypothesis is that high-viscosity hydrocarbon fluid initially surrounds the well screen and restricts fluid movement into the well bore. As fingers of less viscous water break through the hydrocarbon front, less drawdown is required to maintain relatively constant discharge from the well. Unstable displacement of moving hydrocarbon-water fronts is a major factor in limiting the efficiency of petroleum recovery from oil reservoirs (Bear, 1972). Fluid withdrawn from wells W13 and W6 visibly decreased in hydrocarbon content during the pumping period. This fact is significant both with respect to possible future remedial action and procedures that may be developed to monitor chemical changes within the aquifer.

Because each coal-tar compound is soluble to some extent, those in the source material will be dissolved by water moving through the source. The solubility of common coal-tar constituents ranges over at least eight orders of magnitude (pl. 6). Therefore, partitioning between hydrocarbon and aqueous phases will vary widely from compound to compound.

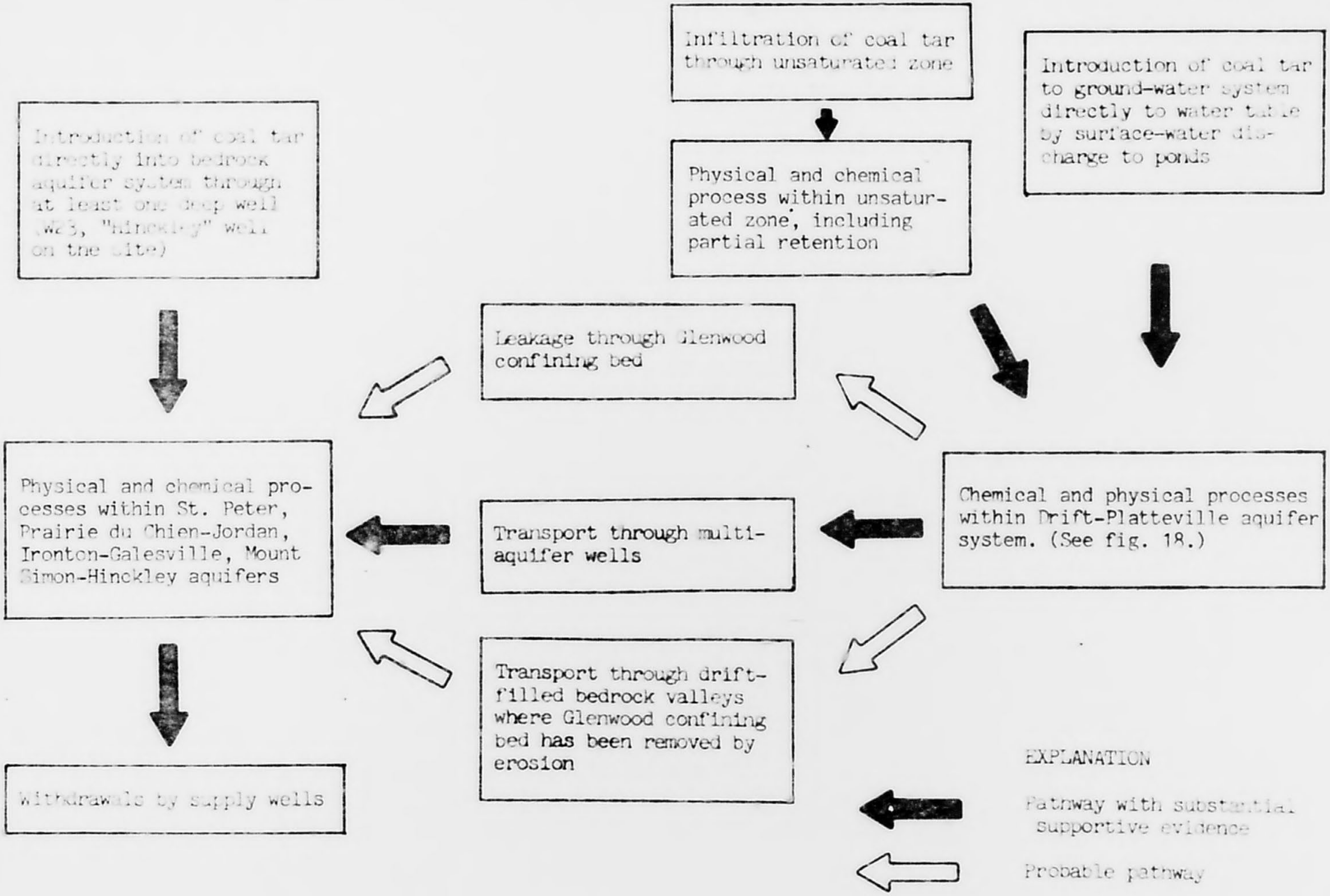


Figure 17.--Tentative conceptual model of the introduction and transport of coal-tar derivatives in the ground-water system

If the hydrocarbons are dissolved, their physical properties become relatively unimportant with respect to their transport, much as the physical properties of, for instance, the solid sodium chloride are relatively unimportant in the transport of sodium and chloride ions in dilute solutions. The chemical properties of the compounds, however, are extremely important in that reactions can remove or alter the compounds. Constituents that tend not to react and to remain in solution, for example chloride ions, are termed conservative. Compounds such as ammonia, which tend to be oxidized to nitrate and adsorbed onto aquifer materials, are termed nonconservative. Many organic compounds are subject to biological degradation, oxidation, reduction, reaction with other organic compounds, and sorption.

The solubility behavior of hydrocarbons is poorly understood. In this report, dissolved constituents of ground water are defined as those that are not removed by filtration through a 0.45 micrometer filter. Many coal-tar derivatives are non-ionic and tend to exist as microscopic aggregates of individual monomers known as micelles. In this report, micelles are considered to be in the aqueous, rather than the hydrocarbon-fluid phase. The following working hypotheses relate to the behavior of micelles:

1. A critical pore size of the porous media exists that, if exceeded, permits micelles to be transported as if they were ideal solutes.

2. A critical pore size exists that, if exceeded, permits micelles to be transported as solutes are, except that if the specific gravity of individual micelles is different from that of water, the micelles will move in different rates and directions than the ground water.

3. Micelles behave as small inclusions of hydrocarbon-fluid phase in the aqueous phase. The proportion of the pore volume that micelles occupy, their surface tension, viscosity, and specific gravity, are all important factors in their transport.

Micelles may be liberated from a hydrocarbon-fluid source and travel through porous media more rapidly than the source itself. At stratigraphic traps caused by reductions in aquifer pore size, the micelles can concentrate and reform a hydrocarbon phase (fig. 18). Both this transport mechanism and movement of hydrocarbon-fluid phase may explain the wide variations in concentration of benzene-extractable compounds reported by Barr (1976) in the drift materials near the site.

A hydrocarbon-fluid phase may be developing at great distances from the site. A particularly likely location is in the valley fill adjacent to the Platteville aquifer along the walls of the buried valleys. The permeability of the Platteville aquifer is due primarily to open fractures and solution channels. These openings are large and may permit the movement of greater quantities of organic compounds than the valley-fill material adjacent to the buried-valley walls. Riha (1977) has shown that some coal-tar compounds can move several miles through aquifers with secondary permeability. Solution-channel carbonate aquifers can transport large amounts of undissolved coal-tar fluids (Sisk, 1977).

Introduction of Coal-tar Derivatives into the Ground-Water System

Coal-tar derivatives have entered the ground-water system in St. Louis Park through three major paths: (1) Spills and drippings on the site, which infiltrated and percolated through the unsaturated zone to the water table (figs. 17 and 18), (2) surface runoff and plant process-water discharge to depressions and wetlands on and south of the site (figs. 17 and 18), and (3) movement of coal tar directly into bedrock aquifers through one or more deep wells on the site (fig. 17).

Spills and drippings from plant operations resulted in extensive contamination of the unsaturated zone on the 80-acre site. The composition of contaminants reaching the ground-water system from surface spills is potentially the most variable of the three major sources. During the 55 years of plant operation, raw coal tar was received from many different suppliers. The composition of each shipment varied. The coal tar was distilled into at least two fractions. The part with a boiling point greater than about 400°C is a heavy tar, which was sold. The part with a boiling point less than about 400°C was used for wood preservation at the site. At various times, other fractions, including naptha and phenol, were distilled from the coal tar. Fuel oil, pentachlorophenol, zinc chloride, and possibly other materials were at times added to the fraction of the coal tar used for wood preservation. The composition of contaminants reaching the ground-water system from spills and drippings on the site likely reflects this variability of sources. Moreover, subareal decomposition of the coal-tar constituents may have produced degradation products dissimilar from those produced in the saturated zone.

Detailed evaluation of the physical, chemical, and biological processes in the unsaturated zone is beyond the scope of this study. Some of the most highly contaminated material above the water table was removed by shallow excavation on the site after the plant was closed in 1972. At times, the water table has been less than 5 feet below land surface over much of the site. The amount of contaminant remaining in the thin unsaturated zone may be small compared with that in the ground-water system.

In the saturated zone, vertical and horizontal movement of hydrocarbon mixtures having fluid properties significantly different from water resulted in irregular distribution of contaminated water and hydrocarbon fluid phases. Chemical analysis of drift cores (Barr, 1976; National Biocentric, 1976a) indicates that contaminant composition and concentration is highly variable. Visible contamination extends at least 10 feet below the water table on the site itself (Barr, 1976).

The second major pathway of contaminants to the ground-water system was through closed surface depressions and water-table ponds on and south of the site. The site is in a topographic low that extends south to Minnehaha Creek. Natural surface drainage was toward the site and south to the Creek. Since at least 1938, however, drainage has been disrupted by roads and other structures. Surface runoff and plant-process water from the site was discharged through ditches and culverts to water-table ponds near well W13. The discharge to the ponds was in excess of the rate of evaporation, resulting in a mounding of the water table and vertical movement of contaminated water and hydrocarbon-fluid phase into underlying, confined drift aquifers. Visible contamination extends at least 50 feet below the water table south of the site near well W13 (Minnesota Department of Health, 1974; Barr, 1976).

Since at least 1938, most of the surface water inflow to the ponds was recharged to the underlying peat and Middle Drift aquifer. The inflow included 30 to 60 gal/min of wastewater (Minnesota Department of Health, 1938) and as much as several hundred gallons per minute of runoff during peak periods. Thi added inflow raised the water level in the ponds and increased vertical leakage. The water table at well W13 was at or slightly below land surface during June 1978 to June 1979, but inspection of areal photographs since 1938 shows that, previously, this area was a pond and that the water table was above the present land surface. The reduction in the water-table mound is attributed to cessation of plant-process water discharges and construction of storm sewers since the plant closed in 1972. Maps in this report show the approximate extent of this pond. However, the pond on the site and the pond south of Lake Street shown on maps in this report are part of the storm-sewer system. They were constructed with impermeable bottom materials to prevent leakage.

The composition of contaminants that entered the ground-water system through the ponds may have been more consistent than the composition of spills and drippings on the site itself. Approximately 2 percent of the raw coal tar as received by the plant was water. The "2-percent cut" was removed from the coal tar and discharged. Discharge from this process may have been enriched with highly soluble compounds. In addition, sodium hydroxide and sulfuric acid were used at various times in plant processing. Between 1940 to 1943, for example, about 80,000 gallons of 70 percent sodium hydroxide was used and discharged to the ponds.

The third major path by which contaminants reached the ground-water system was through at least one well on the site. Well W23 (fig. 13, table 1) was originally drilled in 1917 to a depth of 909 feet but is now 595 feet deep and partly filled with coal tar. A spill may have occurred about 1930. In 1958, a well driller attempted to remove the viscous material by bailing, but was unsuccessful. A core sample of the upper 1 foot of the fill material, which was taken by the U.S. Geological Survey in 1979, consists of sand-sized quartz grains and tar. The amount and maximum depth of the coal tar in the well is unknown.

Well W23 may have been a source of early contamination reported in the Prairie du Chien-Jordan aquifer. The effect it has had on water quality in the Ironton-Galesville and Mount Simon-Hinckley aquifers, if any, is unknown.

Chemical Quality in the Drift-Platteville Aquifer System

Samples were collected from 25 wells in March-April 1979 to define the extent and nature of contamination and the natural hydrogeochemical system on which the contamination is superposed. Data on approximately 50 chemical constituents or fluid properties are presented in table 4.

The fluid pumped from wells may contain both hydrocarbon- and aqueous-fluid phases. However, 23 of the 25 wells sampled yield fluid in which organic carbon is present almost exclusively in what is defined to be a "dissolved" form (see Glossary). The volume of drift in which a hydrocarbon-fluid phase is present is much smaller than the volume contaminated by dissolved constituents. Better criteria are needed to distinguish between dissolved-organic carbon and organic fluids that are immiscible in water. Identification of the hydrocarbon-fluid phase was based on (1) inspection of drift cores, (2) analysis of short-term pumping tests, (3) changes in contaminant concentration in fluid yielded to a well during a single pumping period, (4) visual appearance of fluid yielded to wells, (5) measurement of dissolved, suspended, and total organic carbon of fluid samples and (6) comparison of the measured concentration of individual organic contaminants with their respective solubilities in water. These observations have led to the working hypothesis that movement of coal-tar derivatives in the aqueous phase (whether as solutes or as micelles) is the primary mechanism for contaminant transport in most of the drift-Platteville aquifer system (fig. 18). Because the behavior of micellar coal-tar derivatives may not be critically different from that of solute, an additional working hypothesis can be made -- namely, that most individual contaminant compounds in the aqueous phase behave as nonconservative solutes that are strongly reactive with the porous media (fig. 18). A corollary to these two hypotheses is that contaminant partitioning in most of the contaminated volume of drift and the Platteville aquifer is primarily between the aqueous and the solid phases.

The direction of contaminant transport in the drift-Platteville aquifer system indicated by chemical analyses of fluid pumped from wells is in good agreement with the direction of ground-water flow based on the distribution of hydraulic head. The distribution of three groups of constituents of significance with respect to chemical contamination are illustrated on plates 3, 4, and 5,

1. Sodium - a quasi-conservative, inorganic constituent with potential value as a tracer
2. Organic carbon - a general indicator of contamination levels
3. Nitrogen species - a possible indicator of the influence of biologic processes on the contaminants

Measurement of these indicator constituents is not a substitute for measurement of the concentrations of individual coal-tar derivatives. The indicators are useful, however, in defining the areal and vertical extent of contamination and transport processes.

Contours are shown on plates 3, 4, and 5 to assist the reader in noting general trends. The values shown indicate the composition of fluid pumped from individual wells. Caution must be used in extending these data to interpretations of the relative amount of the constituent sorbed onto the porous media and in hydrocarbon and aqueous fluid phases. More data are needed to define the distribution of the constituents areally, vertically, and between phases. The contours are not meant to reflect concentrations in the volume of drift that is known to contain two fluid phases near wells W13 and W6.

The discharge of sodium hydroxide along with plant-process water has created a plume of elevated sodium concentration. This sodium may be useful in assessing the rate and direction of transport of coal-tar derivatives because it is chemically more conservative than most coal-tar derivatives. Although road deicing chemicals may be an additional source of sodium, it can be shown that they are not the major source. In the Middle Drift aquifer in the volume of greatest contamination near well W13 (pl. 4), the ratio of sodium to chloride in milliequivalents per liter is 2.1 to 1. Road deicing chemicals currently used are typically mixtures of calcium chloride ($CaCl_2$) and sodium chloride (NaCl). Even if only sodium chloride were used, the ratio of sodium to chloride from this source would not exceed unity.

Plates 3 and 5 show that sodium from the plant discharge has reached the Platteville aquifer. The graphs of the percentages of reacting values of major cations (percentage of total milliequivalents per liter of each major cation) shown in plates 4 and 5 further substantiate the conclusion that sodium is being transported through the ground-water system with the organic contaminants. In the Middle Drift aquifer, the major feature of the graph is a downgradient decrease in sodium plus potassium. The potassium concentration is small, and relatively constant (table 4), and does not contribute to this effect.

Plate 3 shows the vertical distribution of sodium and the ratio of sodium to chloride. Well W12 (pls. 3 and 4) is completed in the upper part of the Middle Drift aquifer, and water from the well has a low sodium concentration. The ratio of sodium to chloride, however, is consistent with the uniform, downgradient trend, suggesting dilution by local vertical recharge of water that contains low concentrations of sodium and chloride, as is typical of uncontaminated ground water in the area.

Dissolved and suspended organic carbon concentrations (DOC and SOC) were measured to provide a general assessment of the concentration of organic contaminants in fluid pumped from wells. Hughes and others (1974) have shown that measurement of DOC can be a useful approach if the concentration of organic contaminants is significantly higher than that of natural organic compounds.

The vertical and areal distribution of DOC shown on plates 3, 4, and 5 is remarkably consistent, considering the heterogeneity of the source and the complexity of the hydrogeology and transport mechanisms. The distribution is similar to that of other indicator parameters and decreases systematically downgradient from the source area. Because the concentration of natural organic compounds seems to be 1 to 3 mg/L and because the distribution of contaminants seems systematic, measurement of DOC can be used to estimate the total concentration of organic contaminants in fluid pumped from a monitoring well.

The relationship between the measurements of DOC, SOC, and TOC and the total amount of organic contaminants in the ground-water system is less clear. Firstly, the amount of organic compounds sorbed onto the aquifer materials is not measured. Secondly, wells in those parts of aquifers in which two fluid phases are present may sample both phases. The amount of hydrocarbon-fluid phase pumped from these wells decreases with time as the wells are pumped. This was noted at wells W13 and W6.

During future sampling, attempts will be made to separate the two fluid phases by allowing the heavier hydrocarbon fluid to segregate from the aqueous phase after collection. Separate chemical analyses will be run on each sample. In this way, the chemistry of each of the two fluid phases may be defined, but not their relative proportions in the aquifer.

The fate of the individual coal-tar constituents (see glossary) identified in this study is poorly known. Microbial activity may be a factor in converting the original coal-tar constituents into other compounds (degradation products, see glossary). Sampling for micro-organisms requires specialized procedures (Dunlap and others, 1977) and is beyond the scope of this study. However, the relative distribution of nitrogen species can serve as a general indicator of biologic activity (Baedecker and Back, 1979).

Water entering the general area of contamination in the Middle Drift and Platteville aquifers contains nitrogen primarily in the form of nitrate (pls. 3, 4, and 5). This nitrogen is likely from both natural sources, and the septic tanks and outhouses which were widely used before sewers were installed.

Ground water in the contaminated area contains nitrogen primarily in the form of ammonia. Microbial action as well as purely chemical processes is probably reducing incoming nitrate to ammonia. This hypothesis is supported by the distribution of nitrite (table 4). The ammonia from this source has mixed with ammonia in wastes discharged to the ponds from the plant. In addition, nitrogen-bearing organic compounds present in the coal tar may be degraded to ammonia.

The contours shown for ammonia can be drawn to resemble those of other constituents. Ammonia is strongly adsorbed by clay and silt (Freeze and Cherry, 1979) and the downgradient decrease in concentration may reflect this adsorption. Moreover, some organic compounds are known to interfere with the determination of ammonia concentration (Goerlitz and Brown, 1972). The distribution shown may be due in part to this interference.

Extracts were prepared from 24 of the 25 samples taken for analysis of individual organic compounds. Analyses of the 10 samples collected by the U.S. Geological Survey and completed during the first year of the study and an additional sample collected by the Minnesota Department of Health from well W37 are shown in plate 6. The graphs were prepared by ordering the compounds in decreasing solubility from left to right. This ordering is generally consistent with increasing molecular weight, boiling point, specific gravity, and health risk associated with the compound (pl. 6). Constituents shown have been selected from those for which solubility in water is known, are consistently present in samples, or which have been identified as of particular concern from a health-risk perspective (Minnesota Department of Health, 1977; 1978).

The data should be considered as semiquantitative because the reproducibility of the analyses has not yet been established. The general shape and magnitude of the bar graphs, however, is significant.

Consider the graphs for well W6 (Middle Drift aquifer, in the volume of 2-phase conditions), well W11 (Middle Drift aquifer), well W17 (basal drift complex), and well W101 (Platteville aquifer). Wells W11, W17, and W101 are located on the hydrogeologic section B-B'. In fluid from well W6, phenolic compounds as phenols, the most soluble constituents, are present in the least amounts. The ratio of benzo(a)pyrene (the compound with the lowest solubility of those shown) to phenolic compounds is slightly more than 1 to 1. In the sample from well W101, in the Platteville aquifer near the eastern bedrock valley, the ratio is less than 1 to 1,000. In these four samples, the proportion of highly soluble compounds increases relative to less soluble compounds with increasing vertical and lateral distance from the source in a downgradient direction. These observations lead to the working hypothesis that relatively soluble, low-molecular-weight compounds are moving preferentially through the drift-Platteville aquifer system.

The concentration of contaminants decreases downgradient, presumably owing to dilution, sorption onto the porous media, and chemical and biological decomposition of the original coal-tar constituents. This decrease is in general agreement with trends observed in TOC, DOC, and SOC concentration. The sum of individually measured coal-tar constituents is much less than the apparent contamination as estimated by the DOC concentration except in the sample from well W6. Improvement of the mass balance will require identification and measurement of the concentration of additional coal-tar constituents and degradation products.

Wells W37 and W101 are both completed in the Platteville aquifer near 36th Street and Woodale Avenue and have similar contaminant concentrations. A well completed in the drift, W36 (fig. 3 and table 1), at the same location as W37 was abandoned in about 1972 because its water had a coal-tar taste. This well has not been sampled.

The kinetics and equilibrium concentrations of adsorption and desorption of individual organic compounds onto drift materials is poorly known. Other physical properties of typical coal-tar constituents vary systematically with molecular weight, and their sorption characteristics may vary in a similar fashion. The working hypothesis is that the proportion of an individual compound in the solid phase, relative to the aqueous phase, increases with decreasing solubility. This hypothesis and the degree to which sorption phenomenon can account for the observed concentrations can be better evaluated after comparisons of fluid and core samples and the column experiments have been completed.

The working hypothesis that most of the contaminants are moving in a virtually dissolved form may be disproved. If so, the surface tension, viscocity, and density of hydrocarbon-fluid mixtures may play major roles in transport processes outside the volume of identified two-phase flow.

SUMMARY

Operation of the coal-tar distillation and wood-preserving plant during 1918-72 resulted in a long and complex history of ground-water contamination. Coal-tar derivatives have entered the ground-water system through three major paths. Contamination of the drift resulted from (1) infiltration of spills and drippings on the site itself and (2) recharge from ponds south of the site that received surface runoff and contaminated process water. Contamination of the Prairie du Chien-Jordan and possibly deeper aquifers has resulted in part from (3) coal tar that entered well W23 on the site, which originally was drilled to a depth of 909 feet.

Contaminants in the drift are moving laterally to the east and southeast and vertically into the Platteville aquifer, which directly underlies the drift in much of the affected area. On and immediately south of the site, a hydrocarbon-fluid phase is moving vertically downward with respect to the aqueous phase. Vertical movement from the Platteville aquifer to the underlying St. Peter aquifer is restricted by the Glenwood confining bed, which separates the two aquifers. The Platteville aquifer and Glenwood confining bed have been removed by erosion to the south and east, and the St. Peter aquifer directly underlies the drift. Where the Glenwood confining bed is eroded, contaminated water moves from the drift-Platteville aquifer system into the St. Peter aquifer. Multiaquifer wells and the buried valleys strongly influence the direction of ground-water flow in the Platteville and, therefore, the direction of contaminant transport.

Contaminants in the drift and Platteville aquifers have moved a minimum of 4,000 feet to the east. They reached the vicinity of 36th Street and Wooddale Avenue by 1972 at the latest. Immediately south of this area, the Platteville aquifer and Glenwood confining bed have been eroded. Fluid containing approximately 2 mg/L of organic contaminants may be entering the underlying St. Peter aquifer and valley-fill materials.

Contamination in the major bedrock aquifer of the Twin Cities area, the Prairie du Chien-Jordan aquifer, reached the vicinity of 36th Street and Woodale Avenue as early as 1932. One explanation is that contaminants moved through the aquifer from a coal-tar spill into a deep well (W23) on the site. Contaminants can move fairly rapidly through the Prairie du Chien-Jordan aquifer because the upper part of this aquifer is a solution-channel carbonate rock of high transmissivity and low effective porosity.

The regional gradient in the Prairie du Chien-Jordan aquifer is to the east, but locally the direction of ground-water flow is affected by pumping from municipal and industrial wells and multiaquifer wells through which water flows into the Prairie du Chien. Because the rate and location of pumping is continually changing, the concentration of contaminants reaching individual wells fluctuates.

In 1978, coal-tar derivatives were found to the north of the site in five municipal wells completed in the Prairie du Chien-Jordan aquifer. The most remote of these wells is approximately 2 miles from the nearest probable source of contaminants to the aquifer, well W23 on the site. The northward direction of flow is in agreement with water levels measured in August 1977. Since November 1978, pumping patterns have been altered significantly by shutting down four of the wells that were found to be contaminated. Consequently, the direction and rate of contaminant transport may have been altered.

Five multiaquifer wells, which connect the Prairie du Chien-Jordan aquifer with the overlying aquifers, have been located and evaluated. Flow rates estimated by geophysical logging and inspection with downhole television camera ranged from 20 to 150 gal/min. Each of these wells may have had a significant effect on water levels near the well and, therefore, the local direction of water movement in the aquifers they interconnect. In addition, four of the wells are in areas where the bedrock aquifers are contaminated and were pathways for contaminant transport into the Praire du Chien-Jordan aquifer. Each of these wells has been temporarily or permanently sealed.

The long history of contamination, effect of multiaquifer wells, continually changing pumping patterns, and probable high velocities of contaminant transport through solution channels and fractures in the Platteville and Prairie du Chien combine to produce a complex distribution of contaminants in the bedrock aquifers. It is unlikely that a single, distinct contaminant plume has persisted through time in the Prairie du Chien-Jordan aquifer.

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