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GEOLOGICAL SURVEY

DESIGN OF A NETWORK FOR MONITORING GROUND-WATER QUALITY IN MINNESOTA

By Marc F. Hult

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ABSTRACT

A network for monitoring the quality of water in the 13 principal aquifers in Minnesota has been designed and more than 400 wells and springs selected for sampling. The network organization includes four major elements (1) point sampling, (2) point monitoring, (3) regional monitoring, and (4) site-specific monitoring. These elements constitute monitoring strategies designed to define baseline conditions and monitor major time-and-space trends of more than 60 water-quality parameters. The network has been designed to permit immediate implementation and to incorporate ongoing and future site-specific investigations. However, selection of wells for the site-specific element requires additional detailed work beyond the scope of this study.

SUMMARY

A statewide network to monitor the quality of ground water was designed and more than 400 wells and springs selected for sampling. Thirteen principal aquifers in the State were identified based on previous hydrogeologic studies. Sampling and updating of the network was begun by the Minnesota Pollution Control Agency (MPCA) in March 1978.

The network is designed to (1) obtain data and evaluate major trends in ground-water quality on a statewide basis, (2) define baseline conditions, and (3) permit expansion to include site-specific investigations by the MPCA and other State and Federal agencies.

The overall network design includes four individual design elements:

1. point sampling,
2. point monitoring,
3. regional monitoring, and
4. site-specific monitoring.

Point sampling is essentially nonrepetitive sampling from a single well primarily for the purpose of defining present ground-water quality within each aquifer. Point monitoring is repetitive sampling from a single well or spring to detect changes in ground-water quality with time. Regional monitoring is repeated sampling of a large number of wells or springs in order to define time and space trends in water quality. When implemented, this element will make possible evaluation of previously identified actual or potential contamination problems of regional extent. Site-specific monitoring is repeated sampling at critical times and places in the vicinity of known or potential contamination in order to delineate problems of local extent. Selection of wells for this element of the network is beyond the scope of the project.

Based on site-selection criteria developed for meeting the initial intermediate objectives, more than 400 candidate wells and springs have been identified for sampling. Data on each site are tabulated and initial frequency of sampling and characteristics to be analyzed have been determined.

As data from the network are evaluated, selection of individual sites, sampling frequencies, and characteristics analyzed can be modified as needed. Sites can be added, deleted, or re-categorized as to network element. Present information will need to be incorporated in the network data base.

PURPOSE AND SCOPE

The Minnesota Pollution Control Agency (MPCA) plans to establish and maintain a statewide network for monitoring ground-water quality and has asked the U.S. Geological Survey to assist in its design. The purpose of this report is to design a monitoring network from available data which (1) can be immediately implemented to better define baseline conditions and evaluate major trends in ground-water quality on a statewide basis, and (2) can be expanded to incorporate ongoing and future detailed site-specific investigations of ground-water contamination. Sampling was begun by the MPCA in March 1978 and 101 wells and springs were sampled in the first year.

IDENTIFICATION OF PRINCIPAL AQUIFERS IN MINNESOTA

An aquifer is a formation, a group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of acceptable water to wells and springs. Within this context, nearly the entire State is underlain by aquifers. However, water availability, quality, and demand vary from place to place and what constitutes acceptable water quality and yield for a particular use in one area may be unacceptable in a different area.

The geometry, hydrologic and chemical properties, and actual and potential use of aquifers in Minnesota have been broadly outlined in numerous previous studies. Hydrogeologic data are summarized in 39 U.S. Geological Survey Hydrologic Investigations Atlases. The atlases also contain considerable additional field data and define, in reasonable detail, the principal aquifers of the State. These 39 atlases were used as a basis for a summary of the ground-water resources of Minnesota (Lindholm and Norvitch, 1976) as well as a series of statewide hydrogeologic maps at a scale of 1:500,000 (Kanivetsky, 1979). Aquifers in the Twin Cities area were delineated by Norvitch and others (1974). Figures 1 and 2 show the general distribution of surficial sand and bedrock aquifers respectively.

The Minnesota Geological Survey (MGS) has begun preparation of several county atlases, which include more detailed aquifer definition, and has published a list of wells that penetrate Precambrian rocks (Kanivetsky, 1978). Winter (1974) summarized statewide ground-water-quality investigations. In addition to these areal studies, the U.S. Geological Survey is making a statewide study on the surficial-sand aquifer, a digital-computer ground-water flow model of the Paleozoic aquifer system in Minnesota, and a more detailed model of the Twin Cities Metropolitan area.

Aquifers were identified by compilation and analysis of sample logs, driller's logs, geophysical logs, test augering and drilling, geologic mapping by the Minnesota Geological Survey and U.S. Geological Survey, and soils mapping by the U.S. Soil Conservation Service. Hydraulic characteristics of many of the aquifers were determined by pumping tests, particle-size analyses, and other techniques. Ground-water models of several of the surficial-sand aquifer have been constructed and used to predict aquifer response to increasing water withdrawals.

The U.S. Geological Survey has developed a nationwide aquifer-classification system, which conforms to the criteria of the American Commission on Stratigraphic Nomenclature adhered to by all formally recognized geologic classification systems. The classification used by the U.S. Geological Survey Survey in Minnesota is in substantial agreement with the Minnesota Geological Survey classification. The codes for

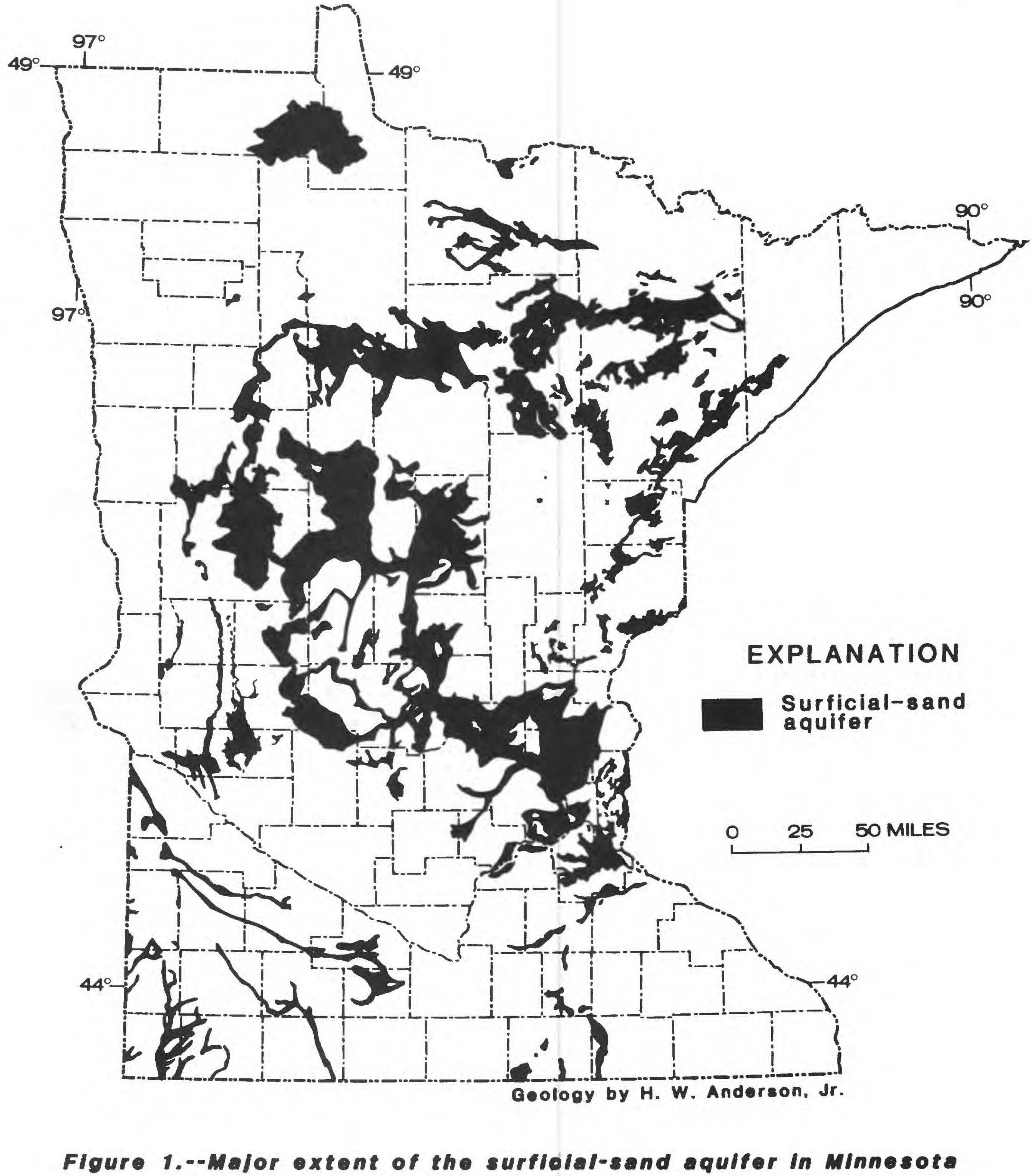

Figure 1.--Major extent of the surficial-sand aquifer in Minnesota

Figure 2.--Bedrock aquifers in Minnesota

aquifers, multiple aquifers, and confining beds in Minnesota used in the U.S. Geological Survey data base are listed in table 1. This system is compatible with and accessible through the STORET system of the U.S. Environmental Protection Agency.

The studies served as the basis for identification of 13 principal aquifers for the monitoring network. The aquifers are listed below. This list is in complete agreement with the current MGS classification (Kanivetsky, 1979) In general, all but the undifferentiated Precambrian rocks and the Paleozoic rocks in northwestern Minnesota constitute principal aquifers. Parts of some principal aquifers have been assigned low priority for sampling based on the site-selection criteria outlined in this report.

Note that some gains in hydrogeologic knowledge or changes in water supplies or demands may result in future reevaluation and changes in the designation of aquifers.

List of classification of principal aquifers in Minnesota

A. Drift aquifers

   1. Surficial sand

   2. Buried sand

B. Bedrock aquifers

   1. Cretaceous, includes weathering products

   2. Paleozoic aquifers, southeastern Minnesota

      a. Cedar Valley-Maquoketa-Dubuque-Galena
      b. St. Peter
      c. Prairie du Chien-Jordan
      d. Franconia-Ironton-Galesville
      e. Mount Simon-Hinckley-Fond du Lac

   3. Paleozoic aquifers, northwestern Minnesota

      a. Red River-Winnipeg

   4. Precambrian aquifers

      a. Sioux Quartzite
      b. Keweenawan rocks
      c. North Shore Volcanic rocks
      d. Undifferentiated Precambrian rocks

Table 1.--U.S. Geological Survey aquifer codes for storage and retrieval of ground-water-quality data in Minnesota

CENOZOIC	
CENOZOIC ERATHEM	100CNZC
QUATERNARY	
QUATERNARY SYSTEM	110QRNR
HOLOCENE	
ALLUVIUM	111ALVM
HOLOCENE SERIES	111HLCN
PLEISTOCENE	
DES MOINES DRIFT	112DMDF
DES MOINES OUTWASH	112DSMO
LAKE AGASSIZ CLAY	112LKGZ
PLEISTOCENE SERIES	112PLSC
PRE-WISCONSIN DEPOSITS	112PRWC
RAINY DRIFT	112RNDF
RAINY OUTWASH	112RNOS
SUPERIOR DRIFT	112SPDF
SUPRRIOR OUTWASH	112SPRO
WADENA DRIFT	112WDDF
WADENA OUTWASH	112WDNO
WISCONSINAN STAGE	112WSCS
TERTIARY	
TERTIARY SYSTEM	120TRTR
MESOZOIC	
MESOZOIC ERATHEM	200MSZC
CRETACEOUS	
CRETACEOUS SYSTEM	210CRCS
UPPER CRETACEOUS	
BELLE FOURCHE FORMATION	211BLFC
COLERAINE FORMATION	211CLRN
UPPER CRETACEOUS SERIES	211CRCSU
CARLILE SHALE	211CRLL
GREENHORN FORMATION	211GRNR
IRON HILL MEMBER	211IRHL
NIOBRARA FORMATION	211NBRR
OSTRANDER MEMBER	211ORDR
PIERRE SHALE	211PIRR
WINDROW FORMATION	211WNDR

Table 1.--U.S. Geological Survey aquifer codes for storage and retrieval of ground-water-quality data in Minnesota--Continued

JURASSIC	
JURASSIC SYSTEM	220JRSC
MIDDLE JURASSIC	
AMARANTH FORMATION	224AMRN
MIDDLE JURASSIC SERIES	224JRSCM
PALEOZOIC	
PALEOZOIC ERATHEM	300PLZC
DEVONIAN	
CEDAR VALLEY-MAQUOKETA-DUBUQUE FORMATION	340CVMD
CEDAR VALLEY-MAQUOKETA-DUBUQUE-GALENA AQUFIER	340CVMDG
CEDAR VALLEY-MAQUOKETA FORMATIONS	340CVMQ
DEVONIAN SYSTEM	340DVNN
DEVONIAN-ORDOVICIAN SYSTEMS	340DVOV
UPPER DEVONIAN	
UPPER DEVONIAN SERIES	341DVNNU
SHELL ROCK FORMATION	341SRCK
MIDDLE DEVONIAN	
CEDAR VALLEY LIMESTONE	344CDVL
CORAL VILLE MEMBER	344CRVL
MIDDLE DEVONIAN SERIES	344DVNNM
RAPID MEMBER	344RPID
SOLON MEMBER	344SOIN
SILURIAN	
LOWER SILURIAN	
SILURIAN-ORDOVICIAN SYSTEMS	357SODV
STONEWALL FORMATION	357STNL
ORDOVICIAN	
ORDOVICIAN SYSTEM	360DDVC
UPPER ORDOVICIAN	
CLERMONT SHALE MEMBER	361CLRM
ELGIN MEMBER	361ELGN
MAQUOKETA SHALE-GALENA DOLOMITE	361MOKG
MAQUOKETA SHALE	361MQKT
CINCINNATIAN	
CINCINNATIAN SERIES	362CNCN
DUBUQUE FORMATION-GALENA DOLOMITE	362DBQG

Table 1.--U.S. Geological Survey aquifer codes for storage and retrieval of ground-water-quality data in Minnesota--Continued

MIDDLE ORDOVICIAN	
DECORAH FORMATION	364DCRH
DUBUQUE FORMATION	364DUBQ
GALENA DOLOMITE	364GLEN
GLENWOOD FORMATION	364GLND
PLATTEVILLE FORMATION	364PLVL
PROSSER MEMBER	364PRSR
STEWARTVILLE MEMBER	364SRVL
ST. PETER SANDSTONE	364STPR
CHAMPLAINIAN	
CUMMINGSVILLE MEMBER	365CMGV
CHAMPLAINIAN SERIES	365CMPL
CARIMONA MEMBER	365CRMN
MCGREGOR MEMBER	365MCGG
PRECATONICA MEMBER	365PCNC
LOWER ORDOVICIAN	
NEW RICHMOND SANDSTONE	367NRCM
ONEOTA DOLOMITE	367ONOT
PRAIRIE DU CHIEN GROUP	367PRDC
SHAKOPEE DOLOMITE	367SHKP
WILLOW RIVER MEMBER	367WLRV
CANADIAN	
CANADIAN SERIES	368CNDN
CAMBRIAN	
CAMBRIAN SYSTEM	370CMBR
UPPER CAMBRIAN	
BLACK EARTH MEMBER	371BCKE
BIRKMOSE MEMBER	371BRKM
CAMBRIAN SYSTEM-PRECAMBRIAN ERATHEM	371CBPB
UPPER CAMBRIAN SERIES	371CMBRU
DRESBACH GROUP	371DRBC
EAUCLAIR SANDSTONE	371ECLR
EAU CLAIRE-MT. SIMON FORMATIONS	371ECMS
FRANCONIA-IRONTON-GALESVILLE FORMATIONS	371FIGV
FRANCONIA SANDSTONE	371FRNC
GALESVILLE SANDSTONE	371GLVL
IRONTON-GALESVILLE-EAU CLAIRE FORMATIONS	371IGEC
IRONTON SANDSTONE MEMBER OF FRANCONIA SS.-GALESVILLE SS	371IGLV
IRONTON SANDSTONE MEMBER	371IRNT
JORDAN-IRONTON-GALESVILLE SANDSTONES	371JIGV
JORDAN SANDSTONE	371JRDN

Table 1.--U.S. Geological Survey aquifer codes for storage and retrieval of ground-water-quality data in Minnesota--Continued

JORDAN-ST. LAWRENCE FORMATIONS	371JSLC
JORDAN-ST. LAWRENCE-FRANCONIA FORMATIONS	371JSTF
LODI MEMBER	371LODI
MT. SIMON-HINCKLEY AQUIFER	371MSHK
MOUNT SIMON SANDSTONE	371MSMN
MT. SIMON SANDSTONE-RED CLASTICS SERIES	371MSRC
MAZOMANIE SANDSTONE	371MZMN
MAZOMANIE-RENO MEMBERS	371MZMR
NORWALK MEMBER	371NRLK
RENO MEMBER	371RENO
ST. LAWRENCE-FRANCONIA FORMATIONS	371SLOF
ST. LAWRENCE FORMATION	371SLRO
SUNSET POINT MEMBER	371SNSP
TOMAH MEMBER	371TOMH
VAN OSER MEMBER	371VOSR
WAUCOBAN	
PRAIRIE DU CHIEN-JORDAN AQUIFER	378PDCJ
PRECAMBRIAN	
ARGILLITE-GRAYWACKE	400AGGK
BIWABIK IRON FORMATION	400BBKF
BELLE PLAINE FORMATION	400BLPL
RASALT	400BSLT
DULUTH COMPLEX	400DCPX
ELY GREENSTONE	400ELY
FOND DU LAC FORMATION	400FDLC
GRANITE	400GRNT
GNEISS-SCHIST	400GSSC
HINCKLEY FORMATION	400HCKL
KNIFE LAKE GROUP	400KFLK
METASEDIMENTARY ROCKS	400MDMR
MINNESOTA VALLEY GRANITE SERIES	400MSVL
METAVOLCANIC ROCKS	400MVCC
NORTH SHORE VOLCANIC GROUP	400NRSR
PRECAMBRIAN ERATHEM	400PCMB
RED CLASTICS SERIES	400RDCC
SIOUX QUARTZITE	400SOUX
VOLCANIC ROCKS	400VLCC
VIRGINIA FORMATION	400VRGN

SUITABILITY AND ADEQUACY OF

PRESENT SAMPLING EFFORTS

Ground-water quality varies continuously in time and space; delineation of this continuum is the broadest goal of sampling programs. The usefulness of individual water-quality analyses in this delineation depends on establishing the relation between point values in both time and space. Given sufficient sampling frequency and density, it is possible to define water-quality variations on a statistical basis. However, definition of the variations can be accomplished much more efficiently if the ground-water flow system is known. By sampling parts of the system that are most significant to ground-water flow, sampling costs are greatly reduced, and the geochemical processes involved are better understood. Successive stages of hydrogeochemical data collection and analysis are used to refine the understanding of the hydrogeochemical system until increasing valid projections can be made of the future operation of the system.

The Minnesota Pollution Control Agency network, as designed, will expand the data base for quality of ground water from principal aquifers in the State, but the network will not provide the additional detailed hydrogeologic information necessary for interpretation of the data. This information, primarily on aquifer characteristics and flow patterns, is of necessity based on past studies and the ongoing State and Federal programs. Therefore, the network has been designed to assure that general interpretations of the water-quality data obtained can be made with available hydrogeologic information. The U.S. Geological Survey Hydrologic Atlas Series and the Minnesota Geological Survey hydrogeologic maps, which show collated information from the Atlas Series at a uniform scale, provide generalized hydrogeologic information on a statewide basis. Additional hydrogeologic information is also available for many areas of the State from more detailed ground-water studies. However, detailed hydrogeologic and geochemical studies will be necessary in some areas where ground-water-quality problems are complex.

Numerous other sampling programs exist in the State. The most significant of these, with respect to a statewide monitoring network, is that of the Minnesota Department of Health. In 1971, 663 municipal water-supply systems (plate 1), depended solely on ground water. More than 2,000 wells have been sampled at least once, and the concentration of major cations and anions, nitrate, iron, and manganese have been published by the Department of Health. Straub and others (1977) compiled these data to develop indices for water quality and ground-water pollution. Since approximately 1972, chemical analyses have generally included selected minor and trace constituents.

In general, however, the Minnesota Department of Health program provides for sampling water directly from the well only once; subsequent samples for the routine monitoring of coliform bacteria, nitrate, and other health-related constituents are taken from taps in the distribution system rather than from the well. Because available information on most municipal wells satisfies the network well-data requirements outlined in this report, periodic resampling of selected municipal supply wells could be included in future expansion of the network. Additional interagency coordination is needed, however, to avoid duplication of effort and to assure compatible sampling and analysis procedures and data-base management.

The Minnesota Department of Health also analyzes samples collected by drillers and private well owners from newly constructed and available wells. The location and construction details of these wells are poorly known. Samples are collected under varying conditions and are analyzed for only a few constituents. These data, therefore, were not considered in design of the network.

The Geological Survey data base presently contains analyses from approximately 2,000 wells collected primarily as part of individual projects. Samples from only a few wells have been analyzed for trace metals, organic compounds, or are from wells that have been sampled more than once. In some areas of intensive irrigation where the Survey has made studies, a network of monitoring wells has been established and resampled at approximately 5-year intervals. Many of these wells are included in the present network. In addition, a network of wells was sampled in 1960-62 in the Twin Cities Metropolitan area to identify baseline water-quality conditions for future resampling. Many of these wells have been abandoned or are now otherwise unsuitable for resampling. The remaining wells, which meet the criteria outlined in this report, have been included in the network.

Plate 1 shows the location of sites where possible changes in ground-water quality have been or are being monitored. The most extensive network is that maintained by the MPCA to monitor the effects of landfills on soil-moisture and ground-water quality. Samples are collected and analyzed by land-fill operators approximately four times a year. Data on a few constituents indicative of contamination from landfills are reported to the MPCA. Future expansion of the statewide network could include sampling by the MPCA at and near the landfills to establish baseline conditions for a greater number of organic and inorganic characteristics.

Detailed evaluation of other monitoring networks shown in plate 1 may indicate the desirability of additional sampling to establish baseline conditions or to better evaluate actual or potential contamination. Such detailed examination is beyond the scope of this report, but, where feasible, future work to expand and maintain the MPCA statewide network can attempt to evaluate and standardize the sampling program.

A major sampling effort, which may provide extensive baseline data on ground-water quality in deeply buried aquifers, is that of the U.S. Department of Energy National Uranium Resources Evaluation Program. Field sampling was begun by the Minnesota Geological Survey in summer 1978, when nearly 2,300 wells were sampled on a 3.2-mile grid spacing in the western part of the State. By 1980, wells in the remainder of the State will be sampled on a 6-mile grid.

Results of laboratory analyses for approximately 40 constituents and data from field measurements of alkalinity, specific conductance, pH, dissolved oxygen, and temperature will be released beginning in 1979.

A selective resampling program could evaluate the accuracy of these analyses. For those areas already sampled, design and implementation of a resampling program could begin when the initial results become available and trends or anomalies are identified. In areas where wells have yet to be selected and sampled, split samples could be taken. Data on radioactive constituents and trace elements, if shown to be consistent with the results of resampling, would greatly increase the amount of information available for these parameters. In the western part of the State, the field measurements and data on major constituents could be useful in delineating the extent of naturally occurring saline water in the buried-sand aquifer, Cretaceous sandstone and Paleozoic aquifers.

OVERALL MONITORING GOAL

The process of designing and implementing a network to monitor ground-water quality is outlined in figure 3. The overall monitoring goal is to define the time and space variation of water quality in the principal aquifers of the State, with greatest detail in areas subject to stress by contamination or withdrawals. Such information will be of value to the MPCA in establishing baseline ground-water quality,

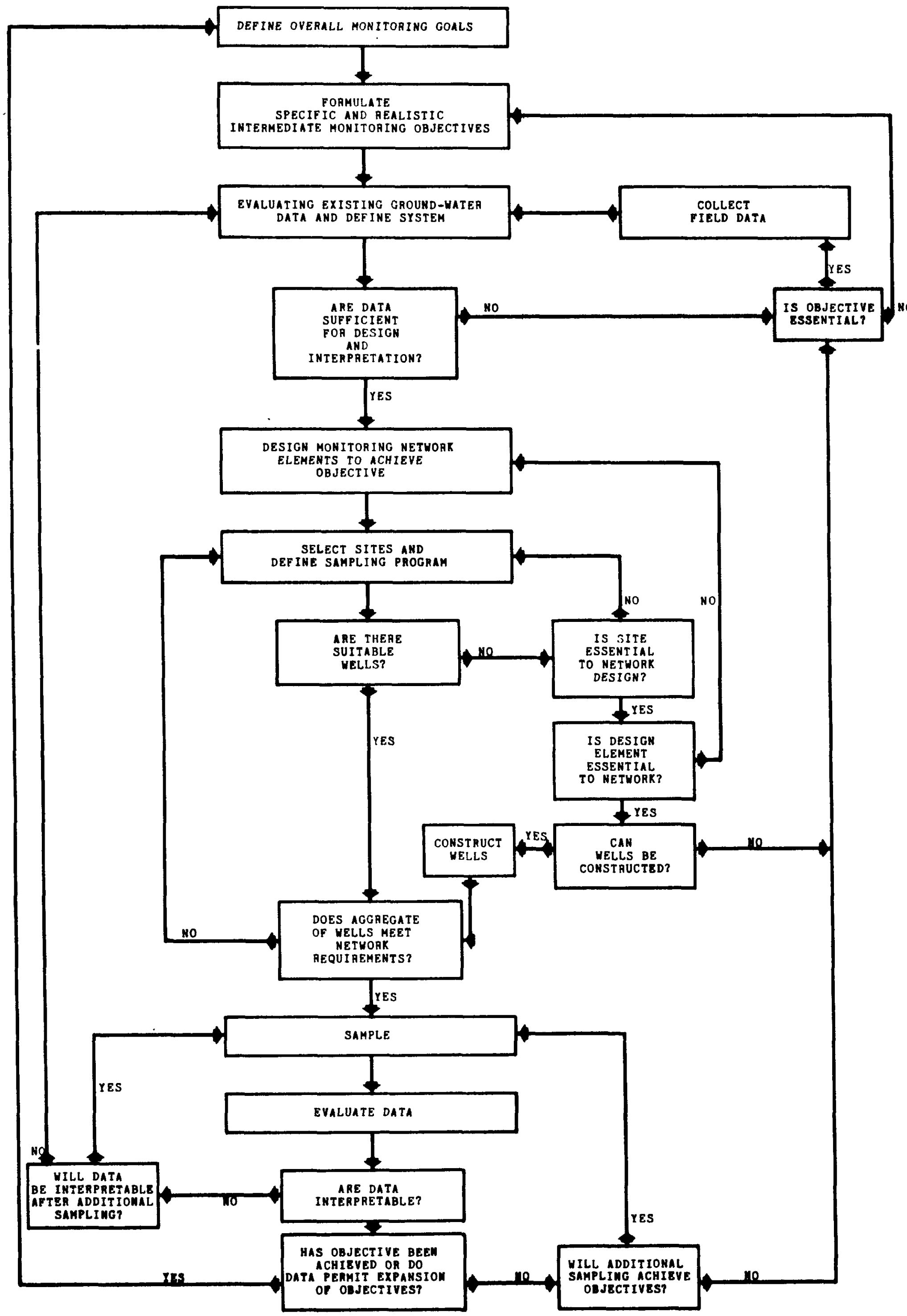

Figure 3.--Generalized description of process of ground-water quality monitoring network design and implementation

assuring protection of drinking-water supplies, assessing the adequacy of waste-disposal systems, detecting ground-water contamination, designing possible remedial measures, and making management decisions. Because restoration of polluted ground water is costly, difficult, and slow, emphasis is needed on prevention of pollution as well as its detection. Only through the ability to predict the effect of man's activity on water quality can deterioration be minimized. Prediction requires that the dynamics of the flow system be understood; in general, available hydrogeologic data suffices only for a description of conditions.

SPECIFIC MONITORING OBJECTIVES

Attainment of the overall goal requires formulation of the specific and realistic intermediate objectives that can be achieved with the available data (fig. 3).

The specific objectives of the network are to:

1. continue definition of baseline conditions in the principal aquifers of the State, with emphasis on water-quality constituents for which specific limits have been established in drinking-water supplies. Few analyses have been made to date of herbicides and pesticides and other individual organic compounds, minor and trace elements, and radionuclides

2. begin a network of key wells to determine trends of water-quality changes with time in local areas of principal aquifers that are significant with respect to water use

3. evaluate areally extensive aquifer contamination where available hydrogeologic data and wells permit.

DESIGN OF NETWORK ELEMENTS

Adequacy of available ground-water data was evaluated and the network monitoring elements were designed to achieve the intermediate monitoring objectives (fig. 3). Each of the four elements shown in table 2 has a definite purpose designed to meet specific monitoring objectives. The scope of each element is based on that purpose and the availability of existing wells and hydrogeologic and geochemical data. The first three elements are within the scope of present monitoring capability and data availability. The fourth element, site-specific monitoring, is problem oriented and requires individual network design based on the specific problem.

Table 2.--Elements of Ground-

Monitoring network element

Element	Sample source	Sampling frequency	Purpose	Scope
Point sampling	Single wells or vertical clusters of wells	Nonrepetitive with selective resampling	Areal synthesis of existing conditions	Statewide with emphasis on areal distribution
Point monitoring	do	Approximately annual sampling	Time trend in areas of major stress	Statewide with emphasis on areas of major stress
Regional monitoring	Groups of wells, springs and(or) streams	Repetitive within hydrologic year and at several year intervals	Statistical approach to problem identification and surveillance	Actual and potential problems of regional extent
Site-specific monitoring	Network of wells	Frequency of resampling dependent on site-specific requirements	Deterministic approach to problem identification, definition, and surveillance, remedial action and monitoring	Site specific (e.g. landfills, spills, chemical stockpiles, etc.)

Major existing activities	Data adequacy for network design	Data on adequacy of existing wells for site selection	Suggested initial sampling emphasis: Percent of wells	Pecent of samples
MGS/DOE: sampling program; U.S. Geological Survey; MDH: sampling of municipal wells	Adequate	Generally adequate	30	15
	Generally adequate except for buried sand aquifers	Generally adequate	20	10
U.S. Geological Survey: irrigation area studies	Generally adequate	Inadequate in some areas, but suitable wells usually can be located by field work	50	75
Site-specific studies by MPCA and other agencies	Generally inadequate	Requires well installation	0	0

Point sampling (table 2) is nonrepetitive sampling from a single well primarily for defining areal baseline water quality within each aquifer. Although concentrations of major and minor cations and anions will be determined, emphasis is placed on defining the statewide distribution of constituents for which limits have been established in drinking water and for which few analyses have been made in the past.

Point monitoring is repetitive sampling from a single well or spring to detect changes in ground-water quality with time. Wells have been selected in areas where such changes are anticipated, such as near areas of major withdrawals.

Regional monitoring is repeated sampling of a large number of wells or springs in order to obtain time and space trends of ground-water quality. By sampling many wells, water-quality data can be broadly evaluated without precise information on the ground-water-flow system in the immediate vicinity of the well, location and nature of sources of contaminants, and volume of the aquifer sampled by the well.

Site-specific monitoring involves repeated sampling at critical places and times in the vicinity of known or potential contamination. A ground-water study is required to define the flow system in order to evaluate the impact of localized stresses, particularily if remedial action or predictive ability are needed. Location and construction of sampling wells is critical and, in general, requirements will not be met by available wells.

Major problems in meeting the intermediate objectives (fig. 3) are (1) all the principal aquifers must be included in the network, (2) initially, approximately 100 samples will be collected per year, (3) the network must be designed from available data without fieldwork, and (4) sampling is limited to existing wells.

The initial individual emphasis of the four network elements is proposed in table 2, and expressed in percentage of wells and percentage of samples. The percentages do not reflect current MPCA site-specific-monitoring activities; only sampling from new sites is indicated. As the objectives of other network elements are met, sampling for the site-specific-monitoring element can be included.

The general approach to network design discussed above can also be focused on specific problems. An example is the impact of highway deicing chemicals on water quality. The elements of such a program would be:

1. Point sampling: sufficient baseline data is available.

2. Point monitoring: sample a limited number of key wells throughout the State several times annually at, for instance, highway rest areas and major intersections.

3. Regional monitoring: locate or construct a large number of wells along roadways where much salt is used and sample at several-year intervals.

4. Site-specific monitoring: test drill and design network to monitor water quality in areas particularly susceptible to contamination and in areas known to be polluted, such as near major stockpiles of salt.

SITE-SELECTION CRITERIA

As indicated in figure 3, site-selection criteria depend on:

1. formulation of specific monitoring objectives and the design of a network to achieve these objectives

2. lacking suitable available wells and the option of constructing them, previous stages of network design must be re-examined

3. the process of site selection is not complete until the aggregate of all wells in the network is satisfactory

4. as sampling proceeds and original monitoring objectives are achieved, sites should be deleted, changed to other network elements, and additional sites should be selected to accomplish new or expanded goals and objectives.

In addition to meeting the purpose and scope as given in table 2, the aggregate of individual wells selected for each network element must also satisfy the following additional requirements (fig. 3):

1. in conjunction with available data, provide a statewide overview of ground-water quality, both with respect to natural constituents and to contaminants

2. include all principal aquifers with an emphasis proportional to present use and the availability of alternative water supplies

3. maximize integration of the network with other water-resources data networks and projects

4. provide data on water quality for studies of regionally significant problems such as those associated with areas of karst, induced or artificial recharge, movement of naturally saline water between aquifers, and extensive irrigation.

Based on these criteria, more than 400 wells and springs were selected and their data tabulated (table 3). Figures 4 through 13 show the distribution of these wells by principal aquifer.

Point Sampling: Distribution requirements

Available information on ground-water-quality has been evaluated to determine areas where additional baseline data are needed. Files were searched for existing wells in those areas and groups of individual wells that best satisfy the following additional requirements considered for selection.

1. wells that are systematically distributed with respect to the regional-flow system (where known)

2. wells from which data will refine the definition of baseline quality and areal changes in water quality

3. wells that are part of present water-resources related data networks

4. wells that are frequently used, to assure that the sample is representative of water in the aquifer.

Suggested initial criteria for judging the adequacy of available data for defining baseline water quality in each aquifer are:

1. at least one sample every 1,000 square miles (approximately one per county)

2. at least three samples in each of the 39 watersheds.

Samples can be analyzed for constituents for which limits have been established in drinking-water supplies, including major cations and anions and selected minor and trace elements, herbicides, pesticides, other organic compounds, radionuclides and biologic constituents. In general, these distribution requirements already have been met for the major cations and anions.

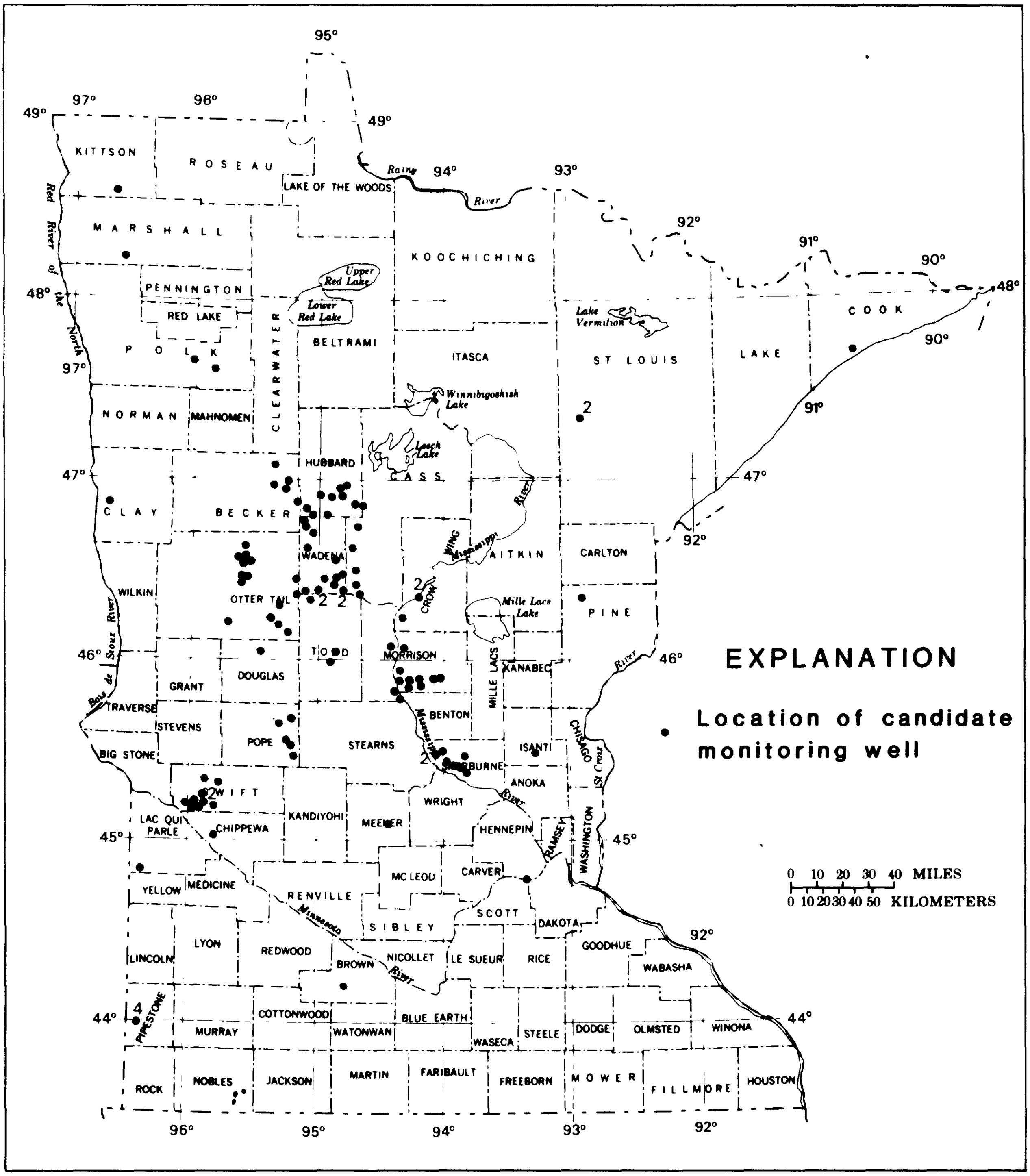

Figure 4.--Location of candidate monitoring wells completed in the surficial-sand aquifer

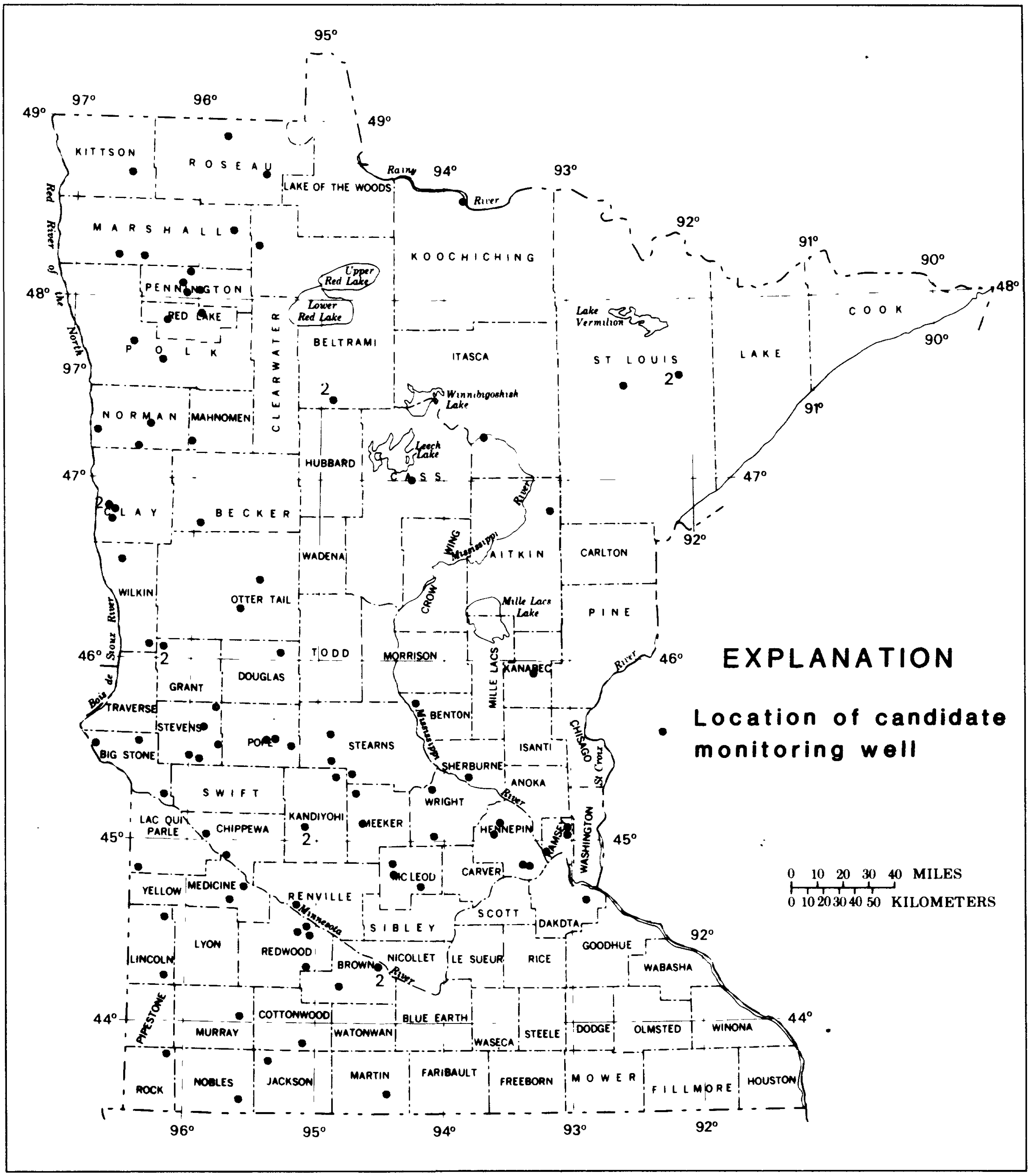

Figure 5.--Location of candidate monitoring wells completed in the buried-sand aquifer

Figure 6.--Location of candidate monitoring wells completed in the Cretaceous sandstone aquifer

Figure 7.--Location of candidate monitoring wells and springs completed in Cedar Valley-Maquoketa-Dubuque-Galena aquifer

Figure 8.--Location of candidate monitoring wells completed in the St. Peter aquifer

Figure 9.--Location of candidate monitoring wells completed in the Prairie du Chien-Jordan aquifer

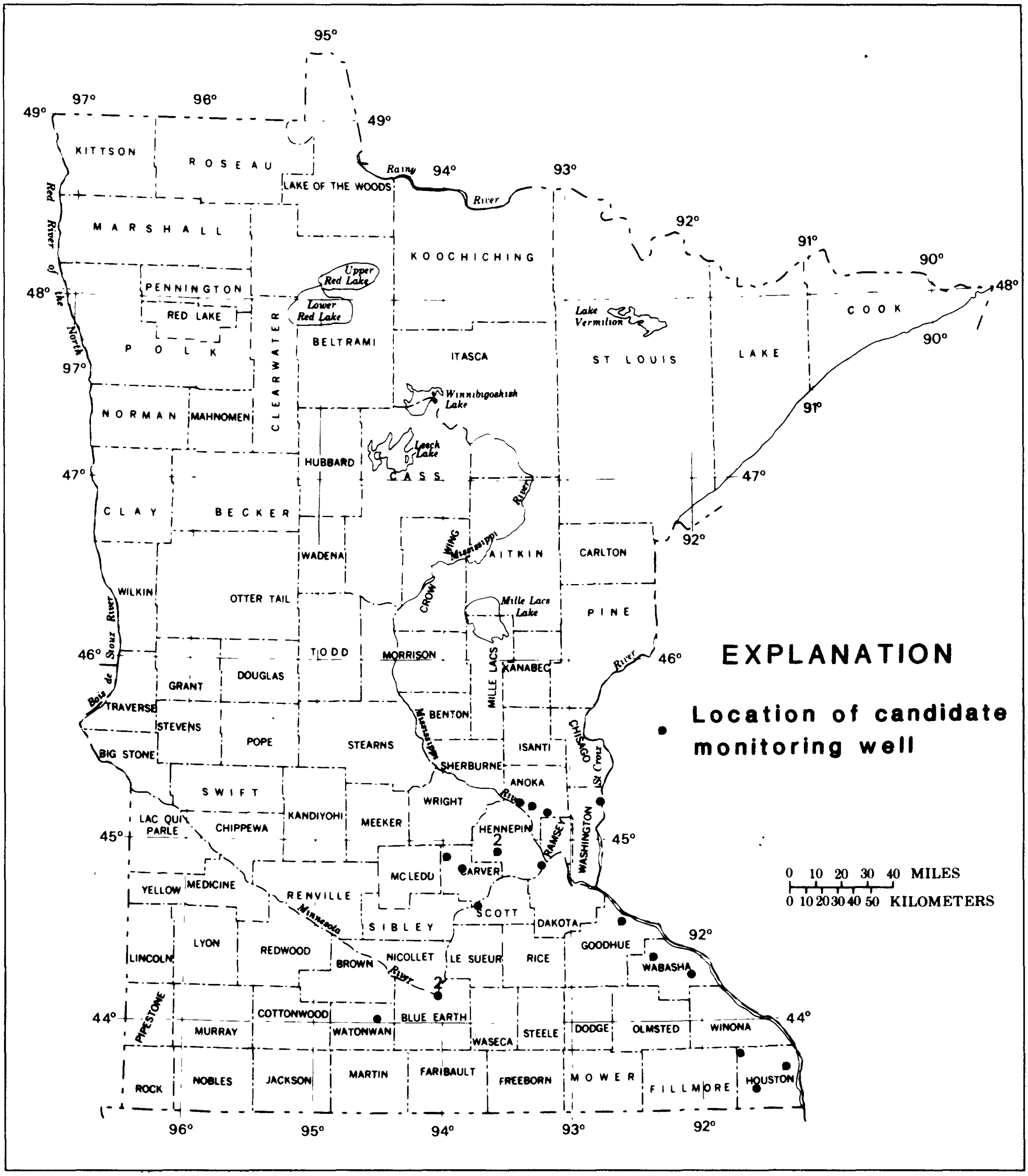

Figure 10.--Location of candidate monitoring wells completed in the Franconia-Ironton-Galesville aquifer

Figure 11.--Location of candidate monitoring wells completed in the Mt. Simon-Hinckley-Fond du Lac aquifer

Figure 12.--Location of candidate monitoring wells completed in the Red River-Winnipeg aquifer

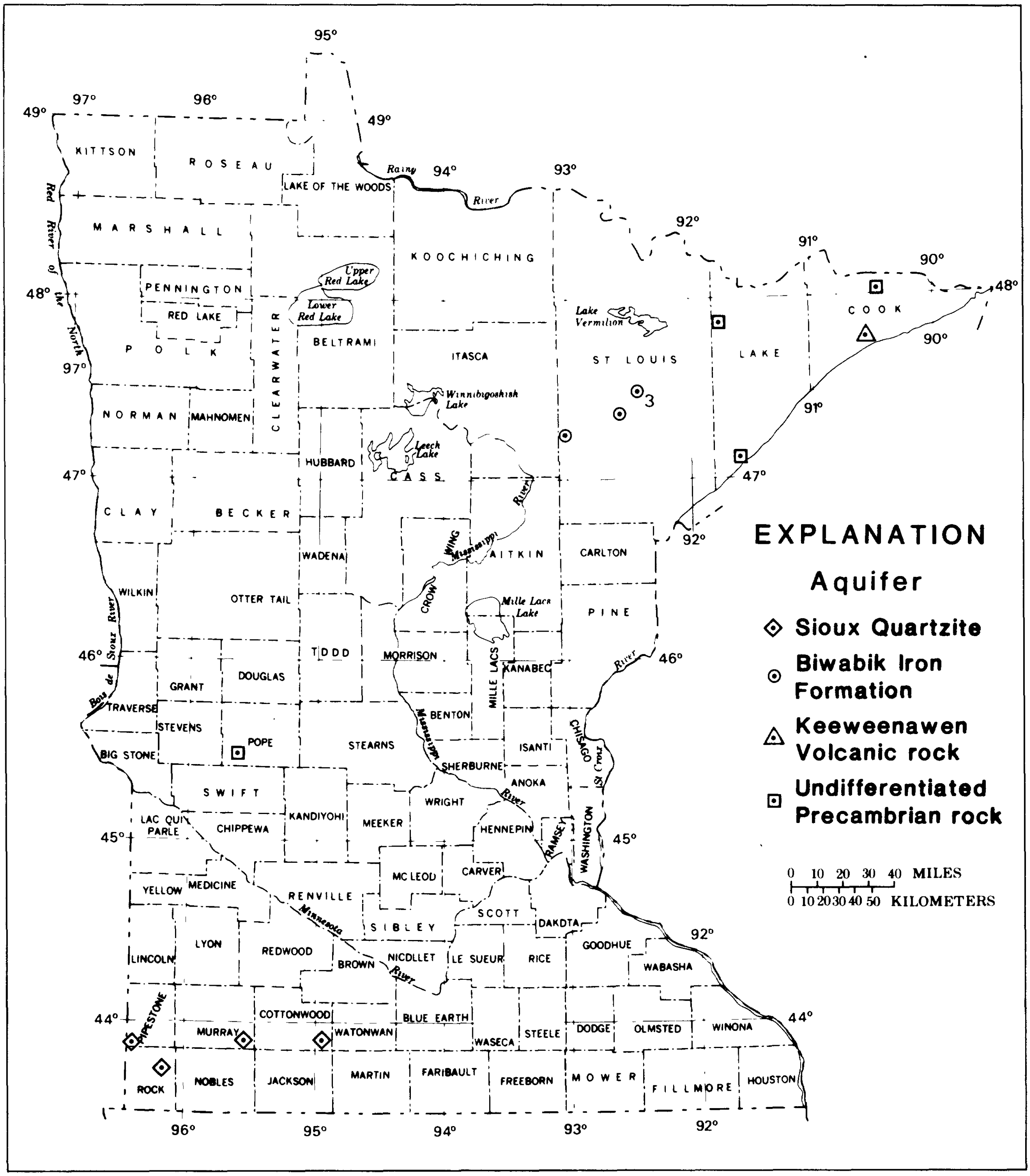

Figure 13.--Location of candidate monitoring wells completed in the Sioux Quartzite, Biwabik Iron Formation, Keewenawan Volcanic rock, and undifferentiated Precambrian rock aquifers

This data distribution will provide only a general description of areal baseline water quality in the principal aquifers. Sampling of approximately 200 wells will be required, which could be accomplished within 3 years at the present rate of sampling.

Point Sampling: Well-data requirements

The initial data requirements for consideration of a well for sampling are:

1. adequate information to enable field personnel to identify the well. This includes the legal description of the location of the well site by township, range, and section to the quarter-quarter-quarter section, and additional data such as location with respect to buildings or roads, owner's or tenant's name, or use of well

2. a geologic log

3. well construction information, such as depth drilled, depth cased, casing type and diameter, and type and length of opening to assure that the well taps a single aquifer and to aid in interpretation of analyses

4. reasonable assurance that the well can be sampled.

Information on the wells has been compiled in tabular form (table 3) as part of the network design. The following information should be obtained for the well at or before the time of sampling, if not initially available.

1. STORET site ID (generally identical to the latitude and longitude of the well location)

2. static water level and date of measurement

3. altitude of water-level measuring point (estimated from topographic map)

4. description of sampling point

5. description of nearby potential pollution sources.

The additional following data are desirable:

1. use of water (domestic, irrigation, stock, and so forth)

2. estimated annual pumpage

3. pumping rate (gal/min)

4. drawdown in well at known pumping rate and after known interval of time.

5. State Permit Application number

6. State Appropriation number

7. Minnesota Unique Well Number.

Point Monitoring: Distribution requirements

Monitoring wells (or springs, and streams as appropriate) have been selected to include principal aquifers in the following areas:

1. cones of depression in major metropolitan pumping centers (for example, Minneapolis, St. Paul, Rochester)

2. large concentrations of irrigation wells

3. where pumping may cause migration of naturally saline water (for example, Red Wing, Winona)

4. the karst region of southeast Minnesota where contamination is known to be widespread

5. areas of induced or artificial recharge from surface water (for example, Minneapolis, St. Paul, Rochester).

Point Monitoring: Well-data requirements

In general, well-data requirements are the same as for point sampling, although greater emphasis has been placed on evaluating the reliability of reported data. MPCA point-monitoring wells may provide sites for additional data collection by the MPCA and other agencies. Examples of future data collection include direct measurement of pumpage, geophysical logging, monitoring of water levels, and construction of additional wells at the site to monitor other aquifers.

In addition to data requirements 1 to 4 listed under point sampling (p. 20), priority has been given to wells:

1. that have been sampled previously

2. for which pumping or water level records are maintained

3. that are of relatively new construction to help assure that the well will be available for repeated sampling and that the casing, screen, or grout have not deteriorated

4. for which geologic samples of well cuttings or a geologist's log are available

5. for which pumping test data are available.

Regional Monitoring: Distribution requirements

Sites have been selected to evaluate three previously identified actual or potential regional problems of water quality degradation. These are: the karst region of southeastern Minnesota; areas of intensive irrigation; and areas of potential and actual migration of saline water owing to pumping.

In the karst region of southeastern Minnesota, ground-water contamination from septic tanks and livestock is widespread in the carbonate aquifers. It is believed that underlying sandstone aquifers are also being contaminated. The Minnesota Department of Health has documented the severity of the problem and has funded projects by five public agencies to examine various aspects of the problem. As yet no areal network has been established to monitor temporal trends. Because the hydrogeology of the karst region is exceedingly complex, the network, as designed, focuses on an area in Mower and Fillmore Counties, where available hydrogeologic data may be adequate for interpretation of the chemical analyses. Thirteen springs and nine wells have been selected for sampling in Fillmore and Mower Counties. In addition to these ground-water stations, surface-water stations can be incorporated into the network and coordinated with present monitoring programs.

Acreage under irrigation is increasing dramatically in Minnesota. Selective resampling of wells by the U.S. Geological Survey suggests a possible increase in nitrate concentration and dissolved solids in some areas. The impact of agricultural chemicals is not completely known, but can be generally evaluated by sampling wells in irrigated areas.

In northwestern and southeastern Minnesota, highly mineralized water occurs in bedrock aquifers. Pumping can cause upconing and lateral migration of water from underlying saline-water aquifers to overlying freshwater aquifers. The future effect on water quality of increasing withdrawals for industry and irrigation is unknown, but regional monitoring can be used to define trends.

Regional Monitoring: Well-data requirements

In general, well-data requirements are the same as for point sampling. However, increased reliance on field checking of the available data will be necessary. Additional wells that meet the criteria will need to be located in the field.

Most domestic wells in the karst region are completed in the uppermost carbonate aquifer. Such wells are suitable if sufficient information about the well is available. Many well owners can provide data on the depth of their well, depth to bedrock, and length of casing.

Irrigation wells that tap the surficial-sand aquifer are nearly ideal for monitoring effects of irrigation on surficial-sand aquifer. Where information on existing high-yield wells in the surficial aquifer were not available, shallow, privately-owned wells and existing U.S. Geological Survey observation wells were selected. In irrigated areas, emphasis has been placed on selecting wells where the water table is within 20 feet of the land surface.

In areas of potential encroachment of highly mineralized water, wells have been selected in aquifers and areas where quality is expected to be most affected by pumping stresses. Suitable wells were located in the Red Wing and Winona areas, but not in northwestern Minnesota.

Site-specific Monitoring:

No criteria have been developed for this element of the network.

NETWORK OPERATIONS

Introduction

Operation of the network will require decisions by the MPCA as to the relative level of effort placed on each individual element of the network. In addition, manpower and funding constraints control the number of sites selected, the frequency of resampling, and the number and choice of constituents analyzed. Suggestions for each of these decisions are included in tables 3 and 4, based on the criteria outlined in table 2 and the experience of 1 year of network operation by the MPCA.

Table 4.--List of suggested constituents and characteristics for field and laboratory measurement

Schedule I.--Minimum list of characteristics suggested for measurement at each sampling of well or spring

Parameter name	STORET number
Calcium, dissolved	00915
Magnesium, dissolved	00925
Sodium, dissolved	00930
Potassium, dissolved	00935
Bicarbonate, dissolved	00440
Carbonate, dissolved	00445
Sulfate, dissolved	00945
Chloride, dissolved	00940
Nitrogen, NO_3, dissolved as N	00618
Phosphorous, dissolved as P	00666
Iron, dissolved	01046
Manganese, dissolved	01056
Carbon, organic, dissolved	00861
Solids, residue @ 180°C, dissolved	70300
Solids, dissolved, calculated sum of constituents	70301
Specific conductance, lab	00095
Cation-anion balance, percent difference	---
PH, field	00400
Temperature, field, °C	00010
Specific Conductance, field	00095
Flow rate, instantaneous, gal/min	00059
Pump or flow period prior to sampling, minutes	72004
Sample source code	72005
Water level, depth below land surface, feet	72019

Table 4.--List of suggested constituents and characteristics for field and laboratory measurement--Continued

Schedule II.--Minimum list of characteristics suggested for measurement at least once at every well or spring

Parameter name	STORET number
Arsenic, total recoverable	01002
Barium, total recoverable	01007
Boron, dissolved	01020
Bromide, dissolved	71870
Cadmium, total recoverable	01027
Chromium, total recoverable	01034
Copper, total recoverable	01042
Fluoride, dissolved	00950
Iodide, dissolved	71865
Lead, total recoverable	01051
Mercury, total recoverable	71900
Nickel, total recoverable	01067
Selenium, total recoverable	01147
Silica, dissolved	00955
Silver, total recoverable	01077
Zinc, total recoverable	01092
Cyanide	00720
Phenolic compounds as phenols	32730
Nitrogen, NH_4, dissolved as N	00608
Nitrogen, organic, dissolved as N	00607
Solids, residue @ 105°C, total	00500
Bicarbonate, field, dissolved	00440
Dissolved oxygen, field	00300

Table 4.--List of suggested constituents and characteristics for field and laboratory measurement--Continued

Schedule III.--Supplementary characteristics suggested for surficial sand aquifers and karst areas

Parameter name	STORET number	Remarks
Methylylene blue active substance, total	38260	
Nitrogen, NO_2, dissolved as N	00607	
Coliform, total		All samples in Karst area; in other areas where potential sources are identified in the field.
Coliform, fecal		
Streptococci, fecal		
Phosphorous, ortho, dissolved as P	00671	Irrigation areas
Phosphorous, total, as P	00665	Karst area
Nitrogen, NO_3, total as N	00620	Karst area
Nitrogen, organic, total as N	00605	Karst area
Amonia, total		
Carbon, organic, suspended	00689	Karst area
Nitrogen, NH_4, dissolved as N	00608	
Nitrogen, organic, dissolved as N	00607	If Schedule II is not used
Bicarbonate, field, dissolved	00440	

It is suggested that additional biologic parameters be added if ongoing research on well-water supplies in the karst area indicates the presence of pathogenic organisms.

Table 4.--List of suggested constituents and characteristics for field and laboratory measurement--Continued

Schedule IV.--Minimum list of characteristics suggested for measurement at least once at each well or spring in point-monitoring element of network.

Parameter name	STORET number
Aluminum, total recoverable	01105
Beryllium, total recoverable	01012
Chromium, hexavalent	02032
Cobalt, total recoverable	01037
Iron, total, recoverable	01045
Lithium, total recoverable	01132
Manganese, total recoverable	01055
Molybdenum, total recoverable	01062
Strontium, total recoverable	01082
Tin, total recoverable	01102
Vanadium, total recoverable	01087
Alpha, total	01501
Alpha, total, counting error	01502
Beta, total	03501
Beta, total, counting error	03502
Potassium 40, total	75038
Potassium 40, total, counting error	75037

Table 4.--List of suggested constituents and characteristics for field and laboratory measurement--Continued

Schedule V.--Herbicides and insecticides

Specific parameters to be analyzed depend on available analytical capability and local use of agricultural chemicals. Where identification of specific compounds in present or past use is not possible, general screening procedures are preferable to analysis of individual compounds.

It is specifically suggested that a general screen be made for triazine-group herbicides from selected wells and springs in surficial-sand and karst areas. The following analyses have been routinely available through the Minnesota Department of Health:

Organochlorine insecticides:	STORET number
O-DDT, total	39370
P-DDT, total	
Endrin, total	39390
Lindane, total	39340
Methoxychlor, total	39480
Toxaphene, total	39400
Chlorinated phenoxy acid herbicides:	
2,4-D, total	39730
Silvex (2,4,5-TP), total	39760

Selection of Water Quality Characteristics for Analysis

Suggested water-quality parameters are categorized for each candidate well in the network (tables 3 and 4). Each sample is to be analyzed for major cations and anions (Schedule I, table 4), and at least the first sample from each well analyzed for selected trace and minor elements (Schedule II, table 4). In those parts of aquifers that are most susceptible to contamination from livestock and septic tanks, such as in areas of near-surface carbonate rocks and the surficial-sand aquifer, an expanded group of nutrient and biologic analyses are suggested (Schedule III, table 4) to indicate the nature and source of possible contaminants.

A supplementary list of trace elements and indicators of radioactivity is suggested for at least the first sample from each point-monitoring well or spring (Schedule IV, table 4). Parameters have been included for which health risks have been established (for example, hexavalent chromium) and which are useful in geochemical characterization (for example, aluminum). Analysis of samples for the suggested indicators of radioactivity (alpha, total and beta, total) and radioactive constituent (potassium-40) will provide general data on which to base future sampling decisions. Selected wells can be resampled for an expanded schedule of radioactive constituents based on these initial analyses and results of samples collected by the Minnesota Geological Survey.

The parameters make up a minimum list; additional analyses can be added to the list as analytical capability becomes available and the need arises. In particular, contamination of ground water by toxic organic compounds is of increasing concern; little is known about the natural distribution of individual organic compounds in ground water. General indicators such as phenols, oil and grease, and dissolved organic carbon can be useful in identifying severe cases of contamination. However, data could be obtained on a statewide basis on individual compounds. For instance, polynuclear aromatic hydrocarbons may be present in significant amounts in natural waters. Where it is anticipated that time-series data will be required in the future for individual organic compounds for which adequate chemical extraction procedures have been developed, it may prove practical to prepare and store extracts for future analysis. For example, in the sand-plain areas, samples could be taken and extracted during one sampling period. A limited number of samples could then be screened for herbicides and pesticides and the remainder of the samples analyzed at a later time for the specific compounds suggested by the screening. Selected herbicides and pesticides are listed in Schedule V, table 4.

The constituents and characteristics listed for each well in table 4 are for the first sample from each site. Ideally, they would not be deleted from successive samples; where specific substances are known to be of particular interest, such as sodium and chloride in areas of encroachment from deep naturally saline aquifers and coliform and nitrate in shallow aquifers, the number of analyses may be reduced. Analyzing each sample for at least major cations and anions and dissolved solids, as well as the other constituents of particular interest, can be useful in identifying measurement errors resulting from sampling methodology, sample preservation, or analytical procedures, as well as changes in the well condition or other factors that may alter the volume of aquifer being sampled. Interpretation of the chemical data with available hydrologic data will be required to isolate actual changes in water quality from such measurement errors.

Frequency of Sampling

A minimum sampling frequency is listed for each spring and well in the network based on its classification by design element and its hydrogeologic setting (table 3). The objective of the point-sampling element to establish general areal trends in natural water quality may be achieved by a single sampling at each well. However, resampling of selected wells should be considered to evaluate measurement reliability. In deeply buried aquifers, resampling even after several months should permit a general evaluation of the sample repeatability. In shallow aquifers that are affected quickly by local recharge and in areas of contamination or pumping stress, sampling and analytical variations may be masked by actual changes in aquifer water quality; spurious variations may be identified by resampling immediately after collection of the initial sample.

When the uncertainty owing to sampling and analytical variations is generally ascertained, the sampling frequency can be reduced. Where stress on the aquifers is cyclical, such as in areas of heavy pumping for irrigation or air conditioning, samples can be taken at different times in the stress cycle.

As samples are collected, analyzed, and changes in chemical quality with time identified, selected wells can be resampled at more frequent intervals to evaluate the changes in greater detail. At point-monitoring and regional-monitoring sites where water quality is changing, more frequent sampling may be warranted immediately. However, frequent sampling to pinpoint the arrival time of contaminants to an individual monitoring well will reduce the total number of sites that can be sampled unless the current level of data collection and analysis is significantly increased.

Sampling Methodology

General procedures used by the U.S. Geological Survey for sampling ground water are outlined in Wood (1976).

The sampling methodology should be followed as closely as possible so that successive samples can provide comparability of time-series data. The sampling point, for instance, should not be changed unless the original is suspected of being inadequate. All sampling mechanisms permit some degree of sample contamination or loss of constituents; the decision to change a sampling point in order to reduce contamination or loss must be balanced with the need for consistency. Likewise, the pumping rate and duration used for the original sample establishes the volume of aquifer sampled. In wells equipped with pumps, the rate of withdrawal will generally be relatively constant from sample to sample.

Data-base Management

The statewide network to monitor the quality of ground water will produce large amounts of data that may be difficult to manage efficiently. In addition, considerable data collected by State and Federal agencies could be incorporated into the network data base, particularly for the point-sampling element of the network.

Site identification numbers suitable for use with the U.S. Environmental Protection Agency STORET and U.S. Geological Survey WATSTORE systems and Minnesota Unique Well Numbers for use with State agency ground-water data bases have been included for sites listed in table 3. Use of these identifiers will permit exchange of information between data bases.

Care should be taken in entering previously collected data into the statewide network data base. In particular, the reliability of the data needs to be assessed and the agency collecting and analyzing the samples and exact measurement identified by STORET parameter number. If a STORET parameter number encompasses more than one measurement technique (for example, field and laboratory values of bicarbonate), inforation on the procedures used can be appropriately recorded.

NETWORK REEVALUATION AND EXPANSION

An integral part of the network design and implementation is evaluation of the data and reevaluation of intermediate objectives (fig. 3). Ideally, sampling sites, classification of sites by element, frequency of sampling, and parameters analyzed would be continuously reassessed and modified as intermediate objectives are met and expanded to achieve overall monitoring goals.

Items to be considered in future expansion of the network include:

1. greater geographic coverage in the karst area as additional detailed hydrogeologic information becomes available and funds and manpower permit the field work necessary to locate and select many wells

2. inclusion of high-capacity wells in the northwestern part of the State in the area of potential saline water encroachment as such wells are drilled, located by additional detailed work, or identified by a current project of the Minnesota Department of Natural Resources to evaluate water use on a statewide basis

3. increased coordination of the statewide network with sampling and monitoring efforts by the MPCA and other State and local agencies, including selective incorporation of data bases to supplement data in the point-sampling element of the network

4. expansion of the network operation to include the site-specific monitoring element by the general process outlined in figure 3. Specifically, this would include (1) defining of objectives, (2) evaluation of available data from site-specific studies and selective incorporation into the statewide data base, (3) locating or constructing wells at locations and in aquifers appropriate to meeting the defined objectives, (4) sampling for the specific items of interest, and (5) evaluating data and reevaluating objectives.

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