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MINNESOTA GEOLOGICAL SURVEY
INFORMATION CIRCULAR 46

AGGREGATE RESOURCES INVENTORY OF THE SEVEN-COUNTY METROPOLITAN AREA, MINNESOTA

D.L. Southwick, M. Jouseau, G.N. Meyer, J.H. Mossler, and T.E. Wahl

Metropolitan Council
Improve regional competitiveness in a global economy

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AGGREGATE RESOURCES INVENTORY OF THE SEVEN-COUNTY METROPOLITAN AREA, MINNESOTA

A joint report of the Minnesota Geological Survey and the Metropolitan Council

by

D.L. Southwick*, M. Jouseau†,
G.N. Meyer*, J.H. Mossler*, and T.E. Wahl*

PART I — INTRODUCTION AND EXECUTIVE SUMMARY

Background

Construction aggregates are sand, gravel, and crushed rock—bulk granular materials that are used in building and landscaping projects of all sizes and kinds. Most of the highest quality aggregate is used in the manufacture of concrete and top-grade asphalt paving. Aggregates of lower quality are used as fill, base-course for roads, and for a myriad of other purposes.

Aggregate quality is determined by the mechanical and chemical properties of the constituent rock particles. In very general terms, the best aggregates for high-end uses contain particles that are strong (resist abrasion and fracturing), chemically inert (do not decompose, swell, or shrink on exposure to air, moisture, or road chemicals; do not react adversely with cement materials), and are of optimum size and shape for the specific engineering requirements. High-strength concrete for heavy-duty use such as highways and airport runways requires aggregate composed of particles that are strong and inert, and also have broken faces; i.e. they are not round and smooth. This broken shape enables the particles to lock up mechanically with one another rather than roll under stress, and improves the durability of the paving.

Minnesota's aggregate industry mines materials of the following three types:

1. Sand and gravel mined from glacial or alluvial deposits. This material, commonly called "natural aggregate," is widespread in the state. Natural aggregate constitutes the largest fraction of aggregate produced. Only some of it, however, is of high-enough quality for the more demanding uses.

2. Crushed carbonate rock (limestone and dolostone or dolomite). This material is mined from bedrock strata in the seven-county metropolitan area and in southeastern Minnesota, and is referred to as "bedrock aggregate" in this report.

3. Crushed "crystalline" rock (chiefly granite, gneiss, quartzite, and basalt or trap-rock) that is mined from bedrock in central, western, and northern parts of Minnesota.

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In addition to aggregate materials that are mined, "recycled aggregate" is made from demolition material that is crushed and cleaned of impurities. In general, recycled aggregate is acceptable for fill, base-course material in roadbeds, and other applications that do not carry demanding quality specifications. Recycled aggregate is not acceptable for inclusion in high-strength, high-durability concrete and asphalt, although it can be used for lower-strength, less-durable concrete and asphalt.

Natural aggregates and crushed carbonate rock (dolostone) are mined within the seven-county metropolitan area. Crushed crystalline rock is imported to the metropolitan area from several sources, primarily from the St. Cloud area of central Minnesota and the Dresser area of western Wisconsin (Fig. 1). Recycled aggregate is produced in the metropolitan area at plants that are typically located at pits or quarries where virgin aggregate materials are produced. Metropolitan recycling operations consume virtually all of the demolition waste materials that are locally available.

Purpose of this Report

Construction aggregate producers and their largest customers in the construction sector have recognized for many years that the aggregate resources available for mining within the seven-county metropolitan area are rapidly diminishing. The ultimate reason for this is urbanization (Fig. 2), which on the one hand increases the demand for construction aggregates, and on the other, tends to remove aggregate-bearing lands from production through land development and zoning decisions that preclude mining. When sources of aggregate are eliminated locally, and become more remote from places of need, the costs of construction rise significantly. This is mainly because of the increased cost associated with aggregate transportation. Cost increases are felt most acutely in large projects such as freeway or airport runway construction that require huge volumes of high-quality aggregate for concrete.

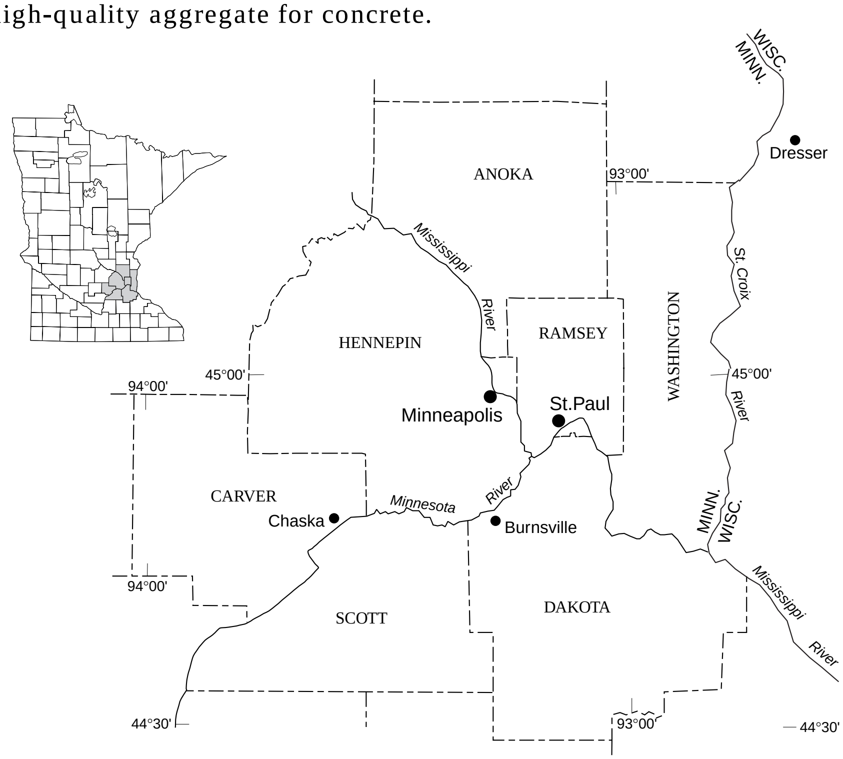


Figure 1. Map of the seven-county metropolitan area showing location of geographic features mentioned in text.

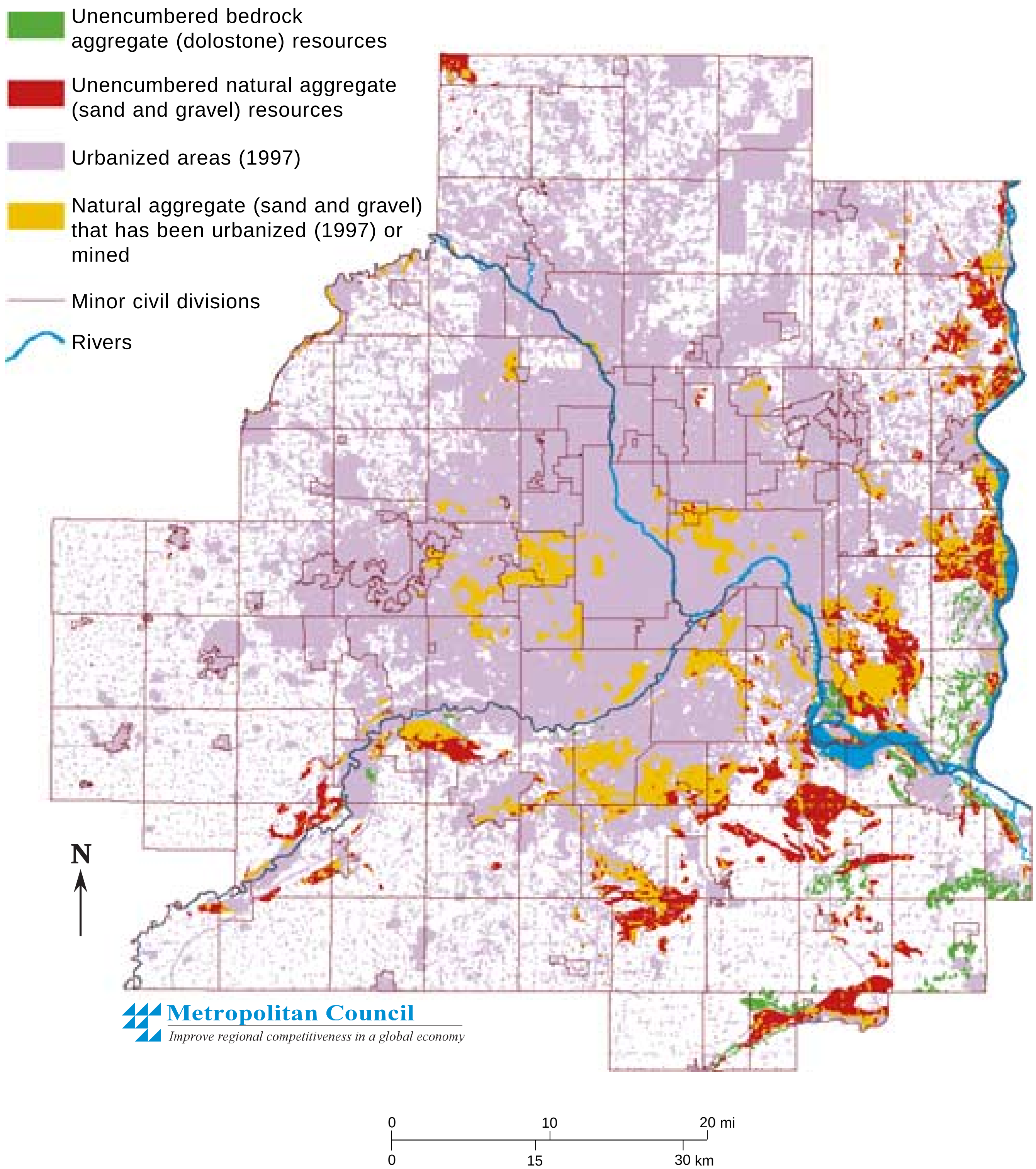


Figure 2. Map showing the extent of urbanization in 1997, and the lands underlain by aggregate resources that were potentially accessible for mining (unencumbered) in 1997. Map also shows areas of natural aggregate that have either been urbanized or mined, as of 1997.

Local decision-makers have become increasingly aware of aggregate-resource issues over the past few decades. Most counties and townships are substantial purchasers of aggregate materials for road building and other purposes, and are therefore sensitive to aggregate costs. Many are also involved in the controversies between neighbors and aggregate producers over the noise, dust, truck traffic, and other environmental impacts (real or perceived) associated with aggregate-mining operations. In Minnesota, including the seven-county metropolitan area, the powers to regulate aggregate mining and associated industrial operations reside largely at the county, city, and township level.

Issues of land-use planning and regulation that apply to the construction aggregates industry need to be resolved. Government entities, the aggregate industry, and citizens of the seven-county metropolitan area all require dependable information on the physical distribution of aggregate resources and the probable economic lifespan of the local resource base. This report and the companion geological maps on which it is based (Meyer and Mossler, 1999) were prepared to meet that need.

The Supply Situation: Geological Generalities

Geological processes established the geographic distribution of natural aggregate and bedrock aggregate resources in the seven-county metropolitan area, and for that matter, everywhere else on the planet. The quality of the material available is also dependant on geological processes. Human needs and desires had no influence on either the effectiveness, or the results of the geological processes. Putting it another way, economically viable deposits of sand and gravel, or bedrock appropriate for crushing, are where they are, whether convenient or not. Furthermore, aggregate resources are not renewable and are only partially recoverable as useful products through recycling. The term geological endowment is used here for the amount of aggregate resources present prior to European settlement (Fig. 3).

Natural Aggregates (Sand and Gravel)

The highest-quality deposits of sand and gravel in the seven-county metropolitan area were laid down about 15,000 to 20,000 years ago by meltwater from a glacial lobe that advanced from the northeast through the Lake Superior basin during the last glaciation. The Superior-lobe gravels contain abundant particles of strong, non-reactive crystalline rock, and only minor amounts of undesirable rock types such as shale or sulfide-bearing slate. During the last glaciation, the southern edge of Superior-lobe ice lay for some time across central Washington, northern Dakota, and eastern Hennepin counties. Thick, coarse deposits of gravel were deposited within and just beyond this ice margin. The most valuable deposits of Superior-lobe gravel are those that are not deeply buried by deposits associated with the younger Des Moines lobe, which moved into the area from the west and northwest a short time after the Superior-lobe ice melted.

Sand and gravel deposits laid down by meltwater from the Des Moines lobe contain particles of shale, and are therefore of lower quality as construction aggregate. Des Moines-lobe deposits are still potentially available to the aggregate industry within the Minnesota River valley in Carver and Scott counties, and in the Cannon River valley in southern Dakota County. Most of the near-surface Superior-lobe gravel deposits in Hennepin and Ramsey counties are now largely depleted or are no longer available for mining. The availability of the best remaining Superior-lobe sand and gravel deposits in eastern Washington and central Dakota counties, is threatened by suburban sprawl.

Bedrock Aggregate (Quarryable Dolostone Bedrock)

The only bedrock deemed valuable as a source of aggregate in the seven-county metropolitan area is dolostone (sometimes termed dolomite) of the Prairie du Chien Group. Magnesian limestone of the Platteville Formation was formerly quarried for aggregate and building stone, but it is no longer used because of its poor mechanical strength and abundant shale partings. Geologic factors that bear on the utility of the Prairie du Chien Group as a source of crushed dolostone include: (1) The thickness of strippable overburden above usable rock, (2) The depth to the water table, (3) The proportion of deleterious clay-rich shale partings, (4) The shape of the bedrock surface; and (5) The amount of natural rock fracturing. Optimally, the overburden should be thin, the water table deep, the shale partings few to none, the bedrock surface essentially horizontal, and the fracturing sufficient to provide some natural breakage yet not so pervasive as to cause problems with the stability of working quarry faces. No quarry site, past, present, or future, meets all these ideal criteria. In all quarries at least one non-ideal geological condition must be dealt with. Geologically suitable bedrock from the Prairie du Chien Group is rapidly being depleted or otherwise made unavailable for mining in the area of historic quarrying along the Minnesota River valley from Burnsville to Chaska. The only volumetrically significant alternative Prairie du Chien bedrock resources are in the southern and southeastern portions of Dakota and Washington counties. These potential bedrock aggregate resources will probably become more valuable when sand and gravel deposits closer to the Twin Cities are mined out.

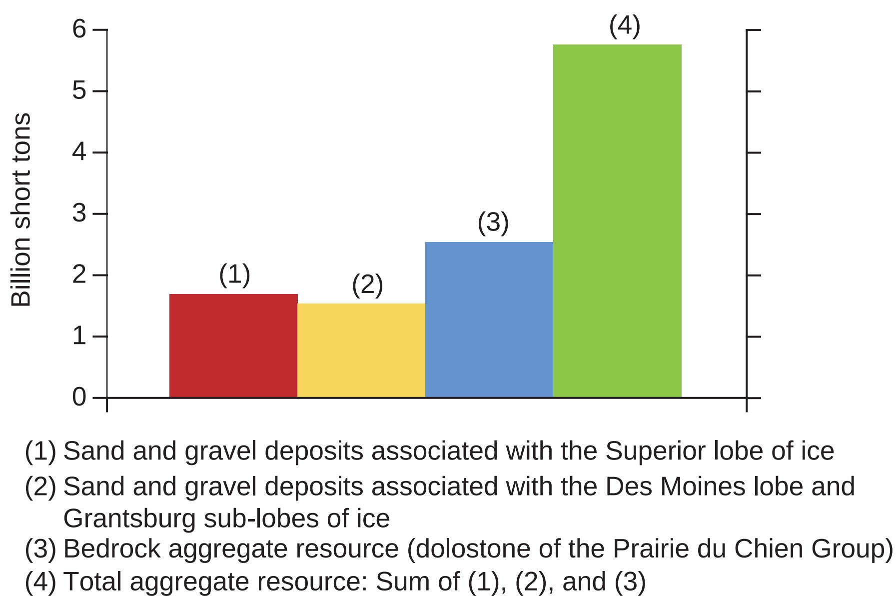


Figure 3. Original pre-1840 tonnage (“geological endowment”) of construction aggregate in the seven-county metropolitan area. The aggregate resources are divided into three geological types (1–3). The total geological endowment (4) was 5.7 billion short tons. See text for discussion.

Resource Estimates

The body of this report presents the technical definition of a mineral resource and the geological and economic criteria required for a sand and gravel deposit, or dolostone bedrock, to meet the definition of a resource in the seven-county metropolitan area. Geological units are mapped (Meyer and Mossler, 1999) so that they incorporate these definitions. To arrive at resource volumes (cubic yards), the areas that are mapped as aggregate resources were multiplied by thickness data. The resulting volumes were multiplied by standard bulk density values (tons per cubic yard) to obtain resource tonnage; the tonnages are adjusted to include wastage factors. Throughout this report the term tons is used for short tons (1 short ton = 2000 pounds). All these calculations were performed by computer, using geographic information system (GIS) software.

Calculated on that basis, the original geologic endowment of construction aggregates in the seven-county metropolitan area, or the amount of material available prior to European settlement in about 1840, was approximately 5.7 billion tons (Fig. 3). That total included approximately 1.7 billion tons of Superior-lobe gravel (excellent to good quality), 1.5 billion tons of Des Moines-lobe gravel (good to fair quality), and 2.5 billion tons of quarryable dolostone (excellent to good quality).

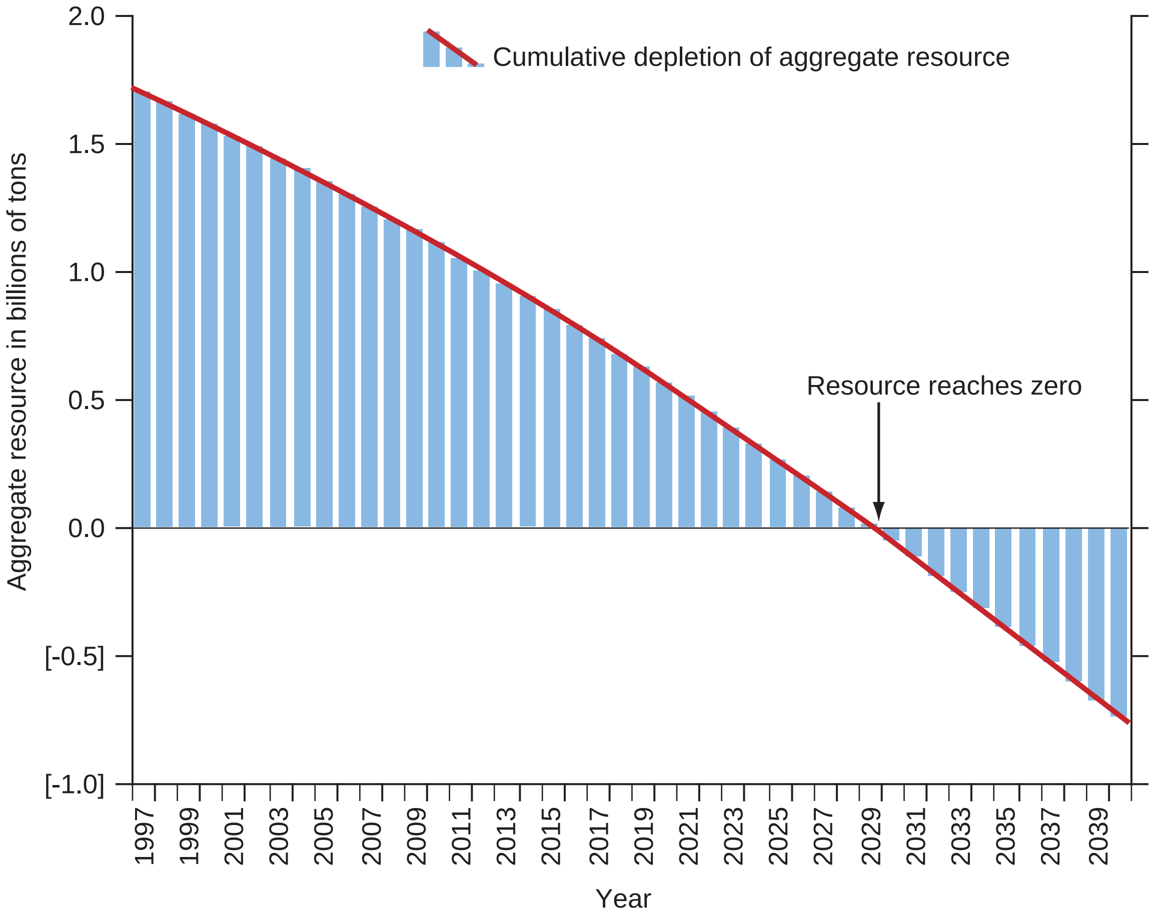


Figure 4. Projected depletion of aggregate resources, 1997–2040. Supplies will be effectively exhausted by 2029. Projection is based on predicted land-use patterns and the 1990–1998 use-rate scenario, as discussed in Part III and Appendix E of this report.

After European settlement began in about 1840, competing land uses and various other socio-economic factors associated with urban growth started to reduce the amount of aggregate-bearing land available for aggregate mining. The rate of reduction of land available for aggregate mining has accelerated sharply in the past 20 years. Reduction is accomplished by (1) covering up the aggregate-bearing lands with surface development that precludes mining (housing developments, stores, industrial parks, etc.), (2) setting open lands aside for non-mining purposes (green spaces, golf courses, wildlife sanctuaries, agricultural preserves, etc.), and (3) dissecting large land parcels into small ones that do not meet the minimum size requirements for modern pit and quarry operations. Dissection occurs when roads, pipelines, powerlines, and other utilities are built that criss-cross otherwise open lands on the fringes of exurbia.

We evaluated these fundamentally geographic effects of urbanization by electronically superimposing digital land-use maps on the digital geologic map. We then calculated the areas of aggregate-bearing lands that are not affected by land uses that rule out aggregate mining ("unencumbered aggregate-bearing land"). We then used a GIS procedure similar to that used for estimating the geological endowment to calculate the tonnage of aggregate available from the unencumbered aggregate-bearing land. These calculations are based on land-use (urbanization) determined from aerial photographs taken in December 1997, and the predicted urban land-use patterns for the years 2020 and 2040. The details of the land-use coverages employed and the GIS procedures by which the unencumbered aggregate resource are estimated are presented in the section on natural aggregate resources in Part II of this report (p. 11), and Appendix D.

In addition to the reductions in available aggregate resources due to factors that are fundamentally geographic (and therefore amenable to analysis by GIS methods), continual mining of aggregate resources (production) further reduces the aggregate resource base over time. We have used production and demographic data from several sources in an attempt to quantify historic production trends, and then to project production and consumption trends into the future. The details of our methods are presented in the section on rate of utilization of aggregate resources in Part III of this report (p. 28), and in Appendix E.

The present resource base for construction aggregates in the seven-county metropolitan area is 1.7 billion tons. This represents a reduction of about 70 percent from the original pre-settlement geologic endowment. We further conclude from our analysis of geographic urbanization patterns and predicted trends in population growth and demand that the construction-aggregate resource base within the seven-county metropolitan area will be effectively exhausted by the year 2029 (Fig. 4). This conclusion pertains to the total supply of the three geological classes of virgin aggregates—Superior-lobe gravel plus Des Moines-lobe gravel plus crushed dolostone. Because gravels associated with the Superior lobe are inherently preferable to Des Moines-lobe gravels for high-strength concrete and asphalt, and are less costly to produce than crushed rock, it is very likely that the Superior-lobe materials will be exhausted first. When this happens, the difference will be made up by imports to the seven-county metropolitan area, and more vigorous development of locally available dolostone resources. Permit applications for mega-quarries on the scale of operations now serving the Chicago, Detroit, or Dallas markets may well become an issue for policy makers in the seven-county metropolitan area in the coming decade.

Neither the aggregate industry nor government entities within the seven-county metropolitan area maintain statistics that differentiate aggregate production by geologic subtype. Therefore we are unable to project the effective lifespan of the Superior-lobe aggregate resources with any precision. However, we can predict with confidence that it will be shorter than the effective life spans of the Des Moines-lobe aggregate resources and the bedrock aggregate (dolostone) resources.

Finally, these conclusions assume that mining parameters such as requisite pit and quarry dimensions, buffer widths, etc., and environmental regulations with respect to ground water, surface water, and air-quality issues, among others, will remain essentially as they were in the 1990's over the period of projection. On balance, the land-policy and regulatory issues that apply to mining and transportation may outweigh all others in determining the effective lifespan of the aggregate resource base in the seven-county metropolitan area.

Major Conclusions

1. The seven-county metropolitan area originally contained about 5.7 billion tons of aggregate resources that meet, or would have met, the specifications of an economically viable resource by today's definitions. This geological endowment included 1.7 billion tons of Superior-lobe gravel (excellent to good quality), 1.5 billion tons of Des Moines-lobe gravel (good to fair quality), and 2.5 billion tons of quarryable dolostone bedrock (excellent to good quality).

2. The present total resource base (year 2000) is approximately 1.7 billion tons.

3. The present resource base will be effectively exhausted by 2029, based on realistic urban-growth scenarios that assume no fundamental changes in present land-use policies or pit and quarry design.

4. It is highly probable that resources of high-quality Superior-lobe gravel will be exhausted before the other aggregate categories. This will lead to increased aggregate imports and more vigorous development of available dolostone bedrock resources.

5. The area of dolostone quarries along the Minnesota River valley from Burnsville to Chaska has very limited potential for expansion. Dolostone resources in southern and southeastern Dakota and Washington counties will become increasingly attractive alternatives for new quarries.

Readers are directed to further conclusions concerning urbanization and land-use policies in Part III of this report (p. 41). Readers are also directed to the Glossary (p. 82), and the aggregate resources maps by Meyer and Mossler (1999).

Funding for this project was provided by the State of Minnesota from accounts administered by the Minerals Division of the Department of Natural Resources, the Metropolitan Council, and the University of Minnesota.

PART II — GEOLOGIC MAPPING AND ESTIMATION OF THE GEOLOGIC AGGREGATE ENDOWMENT

Mapping Methods and Sources of Information

The material presented in this section is intended for use with the maps showing primary sources of construction aggregate for the seven-county metropolitan area that were prepared specifically for this study (Meyer and Mossler, 1999). These maps delineate aggregate resources by geologic type ("natural aggregate" and "bedrock aggregate"), and several attribute classes within each type. The classes are based on quantity and quality criteria that affect the potential viability of the deposits as economic resources (see definition below). The maps also show the locations and boundaries of past and present pits and quarries. The classification schemes applied to natural and bedrock aggregate resources are summarized on the maps (Meyer and Mossler, 1999), and presented on p. 15 and p. 22 of this report.

> The term mineral resource or resource (in which the word mineral is understood) has a precise legal definition. The definition currently accepted by mineral-industry regulators is as follows (Resources and Reserves Committee, 1999, section 18):
>
> A "Mineral Resource" is a concentration or occurrence of material of intrinsic economic interest in or on the Earth's crust (a deposit) in such form and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, geological characteristics and continuity of a Mineral Resource is known, estimated or interpreted from specific geological evidence and knowledge. Mineral Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories. Portions of a deposit that do not have reasonable prospects for eventual economic extraction must not be included in a Mineral Resource. [Emphasis added]
>
> The term Mineral Resource covers deposits which have been identified and estimated through exploration and sampling and from which Mineral Reserves may be defined by the consideration and application of technical, economic, legal, environmental, social and governmental factors.
>
> The term reasonable prospects for eventual economic extraction implies a judgment (albeit preliminary) by the Competent Person in the respect of the technical and economic factors likely to influence the prospect of economic extraction, including the approximate mining parameters. In other words, a Mineral Resource is not an inventory of all mineralization drilled or sampled, regardless of cut-off grade, likely mining dimensions, location or continuity. It is a realistic inventory of mineralization which, under assumed and justifiable technical and economic conditions, might become economically extractable. [Emphasis added]
>
> Where considered appropriate by the Competent Person, Mineral Resource estimates may include mining related assumptions which should be clearly stated.

Production of the geological maps (Meyer and Mossler, 1999) involved the following steps:

1. Transfer of map-unit outlines (polygons) and labels from an earlier aggregate resource study of the seven-county metropolitan area (Meyer and Jirsa, 1984; data as of 1982) to modern digital media that are readable in current geographic information system software (ArcInfo and ArcView).
2. Revision of these previously mapped unit boundaries on the basis of information collected by the Minnesota Geological Survey (MGS) in the course of other mapping projects conducted in the seven-county metropolitan area during the intervening 17 years.
3. Field work undertaken specifically for this study. Some aggregate resources have only been identified recently, and some previously mapped resources have been eliminated.
4. Evaluation and integration of drilling, soil boring, and engineering information collected by public agencies or furnished by private firms, as summarized in Table 1.
5. Auger-drilling of test holes to obtain critical information at sites where available information (item 4) was lacking, sparse, or equivocal. The MGS drilled 106 shallow auger holes on public lands and road right-of-ways in Dakota, Scott, and Washington counties to augment the existing data base. CAMAS, Inc. (now Aggregate Resources, Inc.) voluntarily drilled 20 deep auger test holes on road right-of-ways in Dakota and Washington counties at sites suggested by the MGS. CAMAS also furnished the results of sieve analyses of 18 samples from these deeper test holes.
6. Digital compilation of the geologic maps and underlying data sets (input scale 1:24,000; design output scale 1:100,000). The maps are available as digital files in several formats and as plotter output on paper.

The Minnesota Department of Transportation (MnDOT) provided reports on bedrock quarries as well as pit sheets for active and inactive gravel operations. These reports contain descriptions of borings, sieve analyses, compositional data, and quality tests. All compositional data on sand and gravel reported here (Appendices A and C) come from MnDOT pit sheets, unless otherwise noted. MnDOT also carried out gradation and quality analysis on selected samples collected from borings and pit walls for this study. Geological and engineering data for most of the highway bridge borings and gravel-pit test borings furnished by MnDOT, as well as data from other test borings and water-well logs, are all stored digitally at the Minnesota Geological Survey. Minimum information stored for each boring or well includes depth intervals and descriptions of the materials encountered during drilling, static water level, and geographic location (Wahl and Tipping, 1991). Other pertinent information, such as quality test data, is not stored digitally, but is stored in paper files at MGS. Information sources not listed in Table 1 include published county soil surveys, unpublished University theses, as well as other field studies on open file at MGS. These sources are included in the Bibliography.

Data from the sources listed in Table 1, and from the test holes (item 5 above) as well as that from the additional sources listed in the bibliography, were plotted manually on 7.5-minute topographic quadrangles. Field observations from the many mapping projects carried out previously in the seven-county metropolitan area by MGS staff geologists were also plotted on the 7.5-minute quadrangles. The boundaries of the natural- and bedrock-aggregate resources were drawn on the 1:24,000-scale work maps and generalized where necessary to retain legiblity at the designed compilation scale of 1:100,000. The geologic work maps (1:24,000) were digitized either by scanning or point-and-click methods. The quadrangles for which the 1984 (Meyer and Jirsa) geologic depictions required updating were scanned. For the quadrangles not in need of revision, the point-and-click digital data were used. Map compilation was done digitally, using ArcInfo GIS software. Overall, very little generalization was required to maintain legibility at the compilation scale; only minimal geologic detail was lost in the compilation process.

Natural Aggregate Deposits (Sand and Gravel)

General Geology

Most of the sand and gravel deposits used for aggregate in the seven-county metropolitan area were laid down during the last glacial period, termed the Late Wisconsinan, about 20,000 to 10,000 years ago. Two lobes of ice, the Superior lobe followed by the Des Moines lobe, extended southward through Minnesota (Fig. 5). The ice that forms glaciers picks up (erodes) material from the bedrock that it moves across. These rock fragments are then transported by the ice and associated meltwater streams to ultimately become sand and gravel deposits.

The earlier Superior-lobe ice advance carried rock particles southwestward from the Lake Superior region. Ice of the Superior lobe left behind an irregular arc, or series of prominent hills at its margin, known as the St. Croix moraine, which surrounds the Twin Cities to the west, south, and east. Superior-lobe ice remained or stagnated at this position for some time, and meltwater running off or under the ice produced fan-shaped landforms (outwash fans) composed predominantly of sand and gravel. The outwash fans coalesced into large outwash plains when the ice-transported sediment was sorted and carried away by large, glacier-fed streams. The Rosemount outwash plain in Dakota County contains extensive gravel deposits that were laid down by streams from the melting Superior-lobe ice.

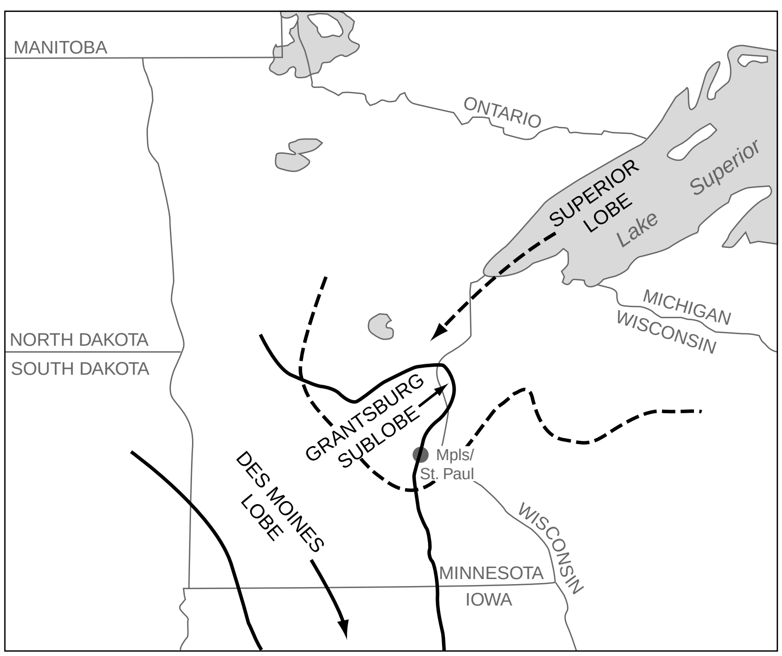


Figure 5. Map of Minnesota showing movement direction and maximum extent of Superior-lobe ice, and the later Des Moines-lobe ice. Note the northeast-directed Grantsburg sublobe of the Des Moines lobe.

Table 1. Sources of public or non-proprietary engineering and geologic data used in this study

Source	Type (and amount) of data
Anoka County Highway Department	County Highway map with old sand and gravel pit locations. No borings logs
Carver County Zoning Administrator	County Highway Map with pit locations. No borings logs
City of Maplewood Department of Public Works	Test borings logs (2,500) for major city projects. Detailed logs with some analyses
City of Minneapolis, Engineering Division, and Department of Public Works Sewer Planning and Design	Schematic diagrams (5,000) of soil and bedrock encountered during investigations and installation of sewers. No test borings or analyses
City of Minneapolis, Inspection Department	Test borings (4,000) for building projects. Detailed logs, some analyses
City of Roseville, Department of Public Works Engineering Division	Test borings (400). Detailed logs, some analyses
City of St. Paul, Department of Community Services Division of Environmental Protection Housing and Building Code Enforcement Division	Test borings (175). Detailed logs; some analyses
City of St. Paul, Housing and Redevelopment Authority	Test borings (700). Detailed logs; some analyses
City of St. Paul, Port Authority	Test borings (825). Detailed logs; some analyses
City of St. Paul, Department of Public Works Engineering Division, Public School System	Test borings (300). Detailed logs; some analyses
Dakota County Highway Department	Location of one active pit; no borings
Hennepin County Bureau of Public Services	Locations of all major gravel production in Hennepin County. No borings
Metropolitan Airports Commission	Test borings. Detailed logs; some analyses
Metropolitan Council Environmental Services†	Water well and test borings logs (1000). Detailed logs; some analyses

† formerly the Metropolitan Waste Control Commission

Table 1. *continued...*

Source	Type (and amount) of data
Municipal Water Departments	Water well logs (in MGS files)
Ramsey County Highway Department	Test borings (500). Detailed logs; some analyses
Scott County Highway Department	Locations of active gravel pits, no borings
State of Minnesota Department of Administration Architectural and Engineering Division	Test borings (600). Detailed logs; some analyses
State of Minnesota, Department of Natural Resources Division of Waters	Water well logs (in MGS files)
State of Minnesota, Department of Transportation Office of Design Services Office of Materials and Research	Sand and gravel pit sheets (329) of active and inactive pits. Test borings (4,650). Detailed logs; some analyses
State of Minnesota, Department of Health Division of Environmental Health	Water well logs (in MGS files)
University of Minnesota Minnesota Geological Survey	Water well logs (35,000)
United States Department of the Interior Bureau of Mines	Test borings (1,500). Detailed logs; some analyses
Minnesota Geological Survey	Water well and test boring logs (in MGS files)
Washington County Highway Department	County highway map with locations of active and inactive pits and quarries
Water-Well Drillers of Minnesota	Water well logs (in MGS files)

When a glacier melts, sand and gravel are carried by meltwater streams that flow on or beneath the decaying ice mass. Although much of the sand and gravel is deposited in front of the melting ice as alluvial fans that coalesce to form outwash plains, as previously explained, large amounts become lodged in crevasses, holes, and tunnels that develop on, within, and beneath the stagnant and melting ice. When the ice finally melts, the sediment that filled these ice-walled depositional sites is left on the landscape as steep-sided hummocks and ridges. Among these so-called ice-contact landforms are kames (gravel hills composed of material deposited in holes and crevasses in stagnant ice) and eskers (sinuous gravel ridges composed of material deposited in tunnels underneath the ice). The gravel deposits of the Maple Grove area are a complex of kames that formed as Superior-lobe ice stagnated and melted.

Before the Superior-lobe ice was completely melted, the Des Moines lobe advanced into south-central Minnesota from the northwest. A small, northeast-directed offshoot of the Des Moines lobe, named the Grantsburg sublobe, overrode the St. Croix moraine in the area to the west and southwest of the Twin Cities (Fig. 5). The Des Moines-lobe ice carried dolostone, granite, and shale fragments picked up in central Minnesota and North Dakota, and it also incorporated material laid down by the earlier Superior lobe. Outwash gravels deposited by meltwaters from the Grantsburg sublobe and the Des Moines lobe therefore contain a varied mixture of sedimentary rock fragments and other rock types derived from northwestern source areas plus fragments of rock types characteristic of the Lake Superior basin.

Meltwater flowing from the retreating ice sheets transported and deposited large amounts of sand and gravel to form terrace deposits along the major drainageways. Several terraces are present along the St. Croix, Mississippi and Minnesota rivers. These terrace deposits are prominent sources of sand and gravel in the seven-county metropolitan area. Pre-Late Wisconsinan ice-contact deposits of Superior-lobe sands and gravels are preserved in parts of Dakota and Washington counties that are beyond the margin of the Late Wisconsinan ice sheet.

In general, the highest quality gravel deposits in the seven-county metropolitan area are in outwash fans, kames, and eskers associated with the Superior lobe. The pebbles and cobbles of basalt, red felsite, gabbro, and metagraywacke in these gravels are typical of bedrock in the Lake Superior area, and tend to be more resistant to weathering and abrasion than the carbonate and shale pebbles derived from northwestern sources. The shale fragments characteristic of the northwest-sourced Des Moines-lobe gravels render aggregate derived from the Des Moines-lobe deposits unacceptable for use in high-strength concrete and asphalt.

Deposit Classification Used in Mapping NaturalAggregates

Sand and gravel deposits of the seven-county metropolitan area are named informally for local areas or geographic features, and identified on the basis of landform type (e.g. kame, outwash, ice-contact, terrace). They are also classified numerically (Table 2) on the basis of physical and geological criteria following a protocol adapted from Schwochow (1974). Several operators and consultants in the aggregate industry, as well as officials of the Materials Division of the Minnesota Department of Transportation and the Minerals Division of the Department of Natural Resources (DNR), aided in establishing criteria for the classification employed here.

Deposits are classified by (1) the percentage of the bulk material retained on the number 4 standard sieve (percentage by weight of particles larger than 4.75 millimeters or 0.187 inch), (2) the workable thickness of sand and gravel, (3) the thickness of overburden above the workable material, (4) the relative position of the water table, and (5) the amount and quality of geological data available for defining the deposit attributes. Thus, each mapped sand and gravel deposit is

Table 2. Summary of criteria used for numerical classification of natural aggregate deposits

Class	Criteria
Class 1.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is more than 40 feet thick. The cover is less than 10 feet thick. The water table is deeper than 20 feet below the land surface. Good subsurface data are available (Good means that deep MnDOT test borings or abundant, detailed water well logs from several drillers are available to assess the attributes of the deposit).
Class 2.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is 10- 40 feet thick. The cover is less than 10 feet thick. The water table is deeper than 20 feet below the land surface. Good subsurface data are available.
Class 3.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is more than 20 feet thick. The cover is less than 10 feet thick. The water table is deeper than 20 feet below the land surface. Subsurface data are limited (Limited in this class means that few borings or water wells are available; soil maps and surficial geology suggest the existence of gravel deposits. Good deposits (classes 1 or 2) are probably present within the mapped area, but their boundaries are uncertain).
Class 4.	Less than 20 percent of bulk aggregate is retained on Number 4 sieve, and/or the sand and gravel deposit is less than 20 feet thick, and/or the cover is more than 10 feet thick. High water table (shallower than 20 feet) may also be a limiting factor. Subsurface data are limited (Limited in this class means that few or no borings or water wells are available, or well logs are too generalized for firm interpretation; soil maps and surficial geology indicate possible sand and gravel deposits. This class generally represents gravel-poor sand deposits or thick sand over gravel, although good deposits may be present in places.)
Class 5.	Less than 20 percent of bulk aggregate is retained on Number 4 sieve, or the sand and gravel deposit is less than 10 feet thick, and/or the cover is more than 10 feet thick. High water table (shallower than 20 feet) may also be a limiting factor. Good subsurface data are available.
Class 6.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is 10 to 40 feet thick and floored by dolostone bedrock. The cover is less than 10 feet thick. The water table is deeper than 20 feet below the surface. Good to fair subsurface data exist (Good in this class means that the presence of dolostone bedrock is generally well established, but the percent of gravel in the deposit above may vary, especially in the larger map areas).
Class 7.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is more than 20 feet thick. The cover is less than 10 feet thick. The water table is shallow; less than 20 feet below the land surface. Good subsurface data are available.
Class 8.	More than 20 percent of bulk aggregate is retained on Number 4 sieve. The sand and gravel deposit is more than 20 feet thick. The cover is less than 10 feet thick. The water table is shallow; less than 20 feet below the land surface. Limited subsurface data exist (Limited in this class means that few borings or water wells are available; soil maps and surficial geology suggest the existence of gravel deposits. Good deposits are probably present within the mapped area, but their boundaries are uncertain and the shallow water table is a limiting factor).

assigned a classification rating of 1 through 8, and a three-letter code representing the informal name and type of the deposit (O for outwash, T for terrace, etc.). For example, map code RSO3 stands for a deposit named the Rosemount (RS) outwash (O) with a classification rating of 3. The various named deposits are described in Appendix A on a county-by-county basis.

The sand and gravel deposits in the seven-county metropolitan area vary markedly in thickness and composition, both laterally and vertically. For this reason, deposits classified on the basis of sparse subsurface information (classes 3 and 8) require more detailed investigations to determine the actual quantity and quality of resource-grade material at any given location.

Estimating the Original Endowment—NaturalAggr egate Deposits

Volume figures for the various aggregate deposits were obtained by multiplying the mapped deposit area (calculated in ArcInfo) by an average thickness assigned to each deposit. Volumes were calculated in cubic yards. Following Hoagberg and Rajaram (1980), volume was converted to short tons (tons) using in-place densities of 1.5 tons per cubic yard for sand and gravel aggregate, and 2 tons per cubic yard for crushed-rock aggregate. According to Hoagberg and Rajaram, aggregate-property evaluations commonly assume processing losses of 50 percent for sand and gravel aggregate, and 25 percent for crushed-rock aggregate. These wastage factors are applied to the gross tonnage figures to give recoverable tonnage estimates for each deposit.

Sand and gravel deposits which are known to be chiefly sand (classes 4 and 5) are not included in the volume and tonnage calculations. Furthermore, the thickness values assigned to the remaining deposit classes are purposely conservative, so as not to over-inflate the implied economic potential of deposits for which the actual thickness or sand / gravel ratios are not well documented. For the volume calculations, we assign an arbitrary thickness of 40 feet for class 1 deposits and 20 feet for classes 3, 7, and 8. The assigned thicknesses are the minimum ends of the thickness ranges for these deposit classes. The defined thickness range for deposit classes 2 and 6 is 10 to 40 feet. For those, an arbitrary average thickness of 20 feet was adopted for the volume calculations. When more precise site-specific data become available for deposit thickness and composition, more precise volume and tonnage estimates will be possible.

Using the definitions, protocols, and methods outlined above, we conclude that the seven-county metropolitan area contained about 3.2 billion tons of commercially viable natural construction aggregate prior to European settlement and the beginning of urban development (Fig. 3, Table 3). In addition, the area originally contained a substantial endowment of dolostone bedrock suitable for quarrying and crushing, which is discussed more fully in the following section of this report.

We emphasize that the calculated endowment of sand and gravel is an estimate that incorporates two very important economic assumptions in addition to the geological facts and assumptions already discussed. The economic assumptions, which are valid in today's marketplace, are (1) that deposits composed predominantly of sand have no market value, and (2) that deposits buried more deeply than 10 feet by non-marketable overburden are uneconomic to mine. If future market conditions should ascribe value to sand deposits or permit the economic extraction of more deeply buried gravel deposits, the resource base for natural aggregates in the seven-county metropolitan area would increase significantly. The very large volumes of material in deposit classes 4 and 5, now excluded from resource computations, would then have economic value and would be considered a resource.

Table 3. Tonnage of aggregate resources* ("geological endowment") in the seven-county metropolitan area prior to urbanization

On land parcels of	Raw resource (billions of short tons)			
	Sand and gravel			
	Superior-lobe deposits	Des Moines lobe deposits	Quarryable dolostone	Total
all sizes	1.71	1.51	2.51	5.73
20 acres or more	1.70	1.50	2.30	5.50
40 acres or more	1.68	1.47	2.16	5.31
80 acres or more	1.64	1.42	1.86	4.92
160 acres or more	1.57	1.31	1.49	4.37
320 acres or more	1.49	1.18	0.87	3.54

* Resources that meet or would have met the definition of resources in today's marketplace

Bedrock Aggregate Resources (Crushed Dolostone)

General Description and Discussion of the Bedrock Geology

The near-surface and exposed bedrock in the seven-county metropolitan area consists of sandstone, shale, limestone, and dolostone. These rocks are formed from sediments deposited in seas that covered this area about 520 to 450 million years ago. These bedrock units form essentially flat-lying layers, or strata, and are divided into the following formations (in descending order, i.e. going downwards from younger rocks to older rocks): Decorah Shale, Platteville Formation, Glenwood Formation (shale), St. Peter Sandstone, Prairie du Chien Group (dolostone and sandstone), Jordan Sandstone, St. Lawrence Formation (shale and dolostone), and Franconia Formation (sandstone and shale). Descriptions of these units and their relative stratigraphic positions are shown in Figure 6.

The principal sites of bedrock exposure in the seven-county metropolitan area are the walls of stream valleys that were cut during episodes of high glacial-meltwater flow, or by ordinary stream erosion since the end of the last glaciation. Where bedrock is not exposed at the present-day land surface, it is mantled by glacial sediments. The buried bedrock surface is very uneven; it is composed of steep-sided valleys and relatively flat-topped, plateau-like interfluves. The valleys were eroded into the bedrock prior to the most recent glacial advances. Sediments deposited by the glaciers typically fill these bedrock valleys and cover the plateau-like surfaces. Bedrock units composed of limestone or dolostone are more resistant to erosion than those composed of sandstone or shale. Consequently, limestone- and dolostone-bearing formations tend to cap bluffs and undergird broad upland plateaus wherever they are close to the land surface.

Regionally, the bedrock strata beneath the seven-county metropolitan area dip very gently (less than 0.1 degree) toward the central Twin Cities, forming a dish-shaped structure known as the Twin Cities basin (Fig. 7). This general pattern is locally modified by folds and faults. As a result of the basinal structure, the younger (stratigraphically higher) bedrock formations are either exposed, or form the uppermost buried bedrock near the center of the basin. The progressively older (stratigraphically lower) formations are exposed, or form the shallowest buried bedrock toward the basin periphery.

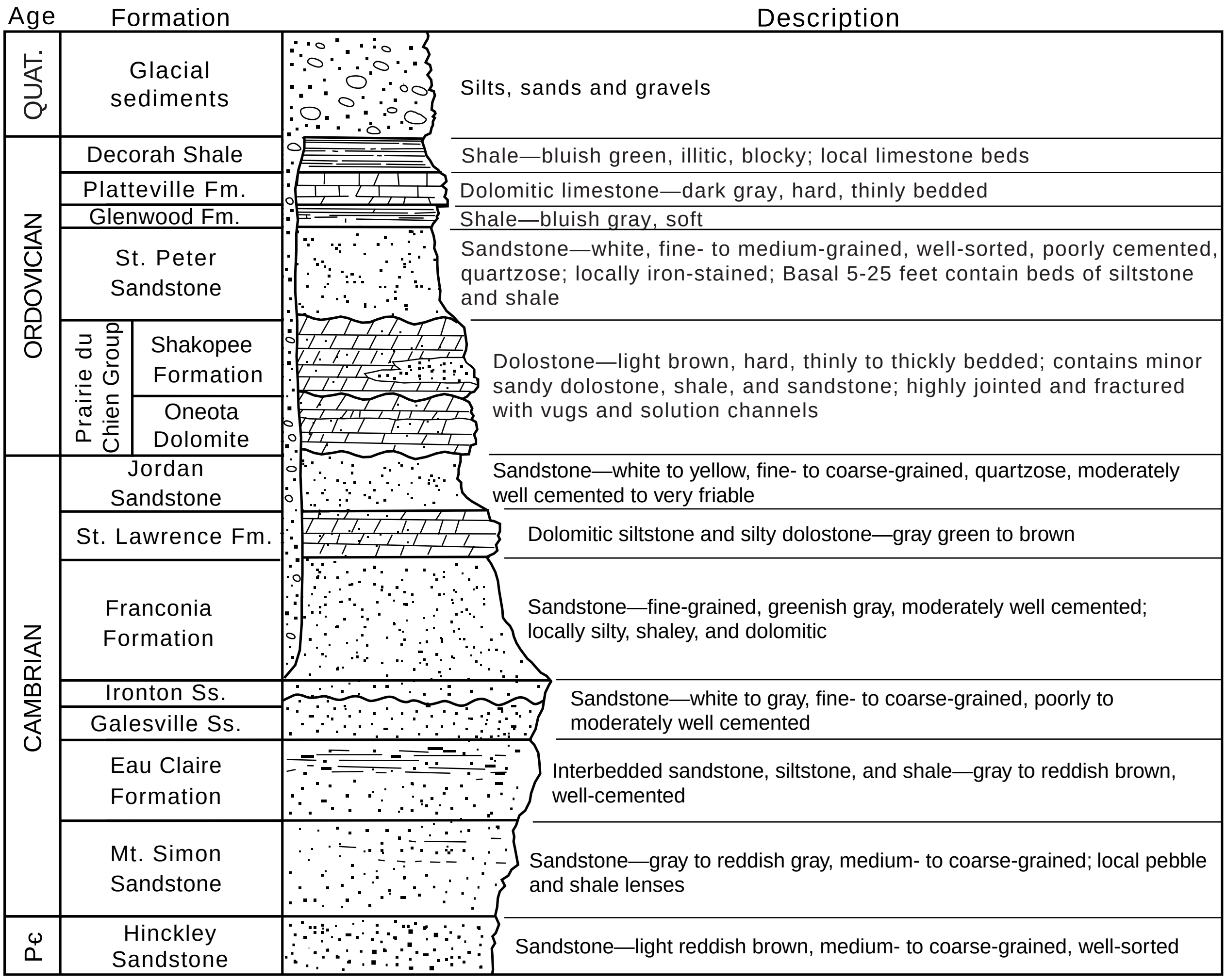


Figure 6. Generalized geologic column for the seven-county metropolitan area. The geologic unit of primary interest as a source of crushed stone is the Prairie du Chien Group, which consists dominantly of dolostone (also called dolomite). It is divided into two formations (Shakopee Formation and Oneota Dolomite) that differ from each other in details of composition, texture, and structure. The Prairie du Chien Group lies stratigraphically between sandstone units (Jordan Sandstone and St. Peter Sandstone) that have virtually no value as sources of aggregate but are very valuable sources of ground water.

Figure 7 (on page 19). Simplified geologic map and cross section showing bedrock in the seven-county metropolitan area. Dolostone of the Prairie du Chien Group is the "uppermost bedrock" within the pale blue areas, and is within 10 feet of the land surface in the areas shown in dark blue. The cross section is a vertical slice (looking towards the northeast) along the line A–A' that shows the subsurface positions of the Prairie du Chien Group and other bedrock formations in the Twin Cities basin. Areas where the uppermost bedrock is St. Peter Sandstone, Glenwood Formation, Platteville Formation or Decorah Shale are shown in pale yellow. The glacial sediments (overburden or cover) are only shown on the cross section.

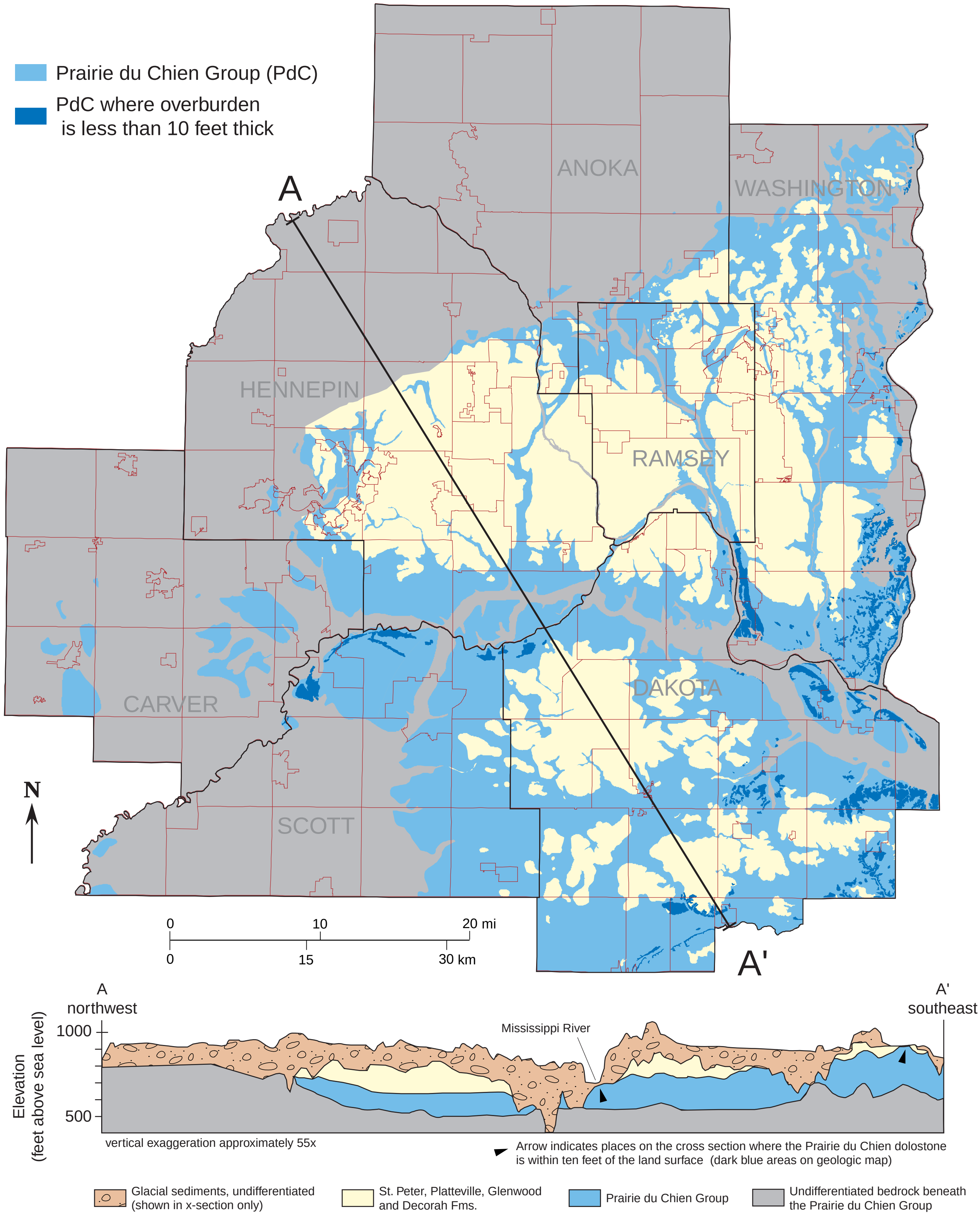


Figure 7 (caption on p. 18)

The requisite qualities for crushed rock (bedrock aggregate) are (1) proximity of the deposit to market, (2) sufficient quantity, and (3) favorable mechanical properties of the rock, including dimensional stability, hardness, tensile strength, as well as minimal fractures and bedding planes (Schenck and Torries, 1975). The most desirable bedrock contains large quantities of hard, finely crystalline, thickly bedded limestone or dolostone, that is near the land surface and near the market area. The Prairie du Chien Group is the only bedrock unit that meets these criteria in the seven-county metropolitan area.

The Platteville Formation was classified as a resource by Meyer and Jirsa (1984) in the original inventory of aggregate resources in the seven-county metropolitan area, but is no longer considered suitable for use in concrete, bituminous surfacing, or rip-rap. This is chiefly due to its high content of insoluble residue. Therefore it does not enter into resource calculations for this study. The only other formation shown on the stratigraphic section (Fig. 6) that contains significant dolostone and is fairly well indurated, is the St. Lawrence Formation. However, the St. Lawrence is not present at shallow depths in sufficiently large areas within the seven-county metropolitan area, and its dolostone portion contains unacceptably high amounts of insoluble residue (clay, silt, sand). The high insoluble residue content contributes to undesirable chemical reactions between St. Lawrence-derived aggregate and the cement materials in concrete. The other bedrock strata or formations (Fig. 6) are composed of poorly indurated sandstone and shale; they are not suitable sources for crushed-rock aggregate.

Geology of the Prairie du Chien Group

The Prairie du Chien Group consists of thin- to thick-bedded dolostone (the beds range from thinner than one inch to thicker than three feet), sandy dolostone, and sandstone. The group attains a maximum thickness of 280 feet in the southern and southeastern parts of the seven-county metropolitan area. The dolostone and sandy dolostone beds range from flaggy to highly fractured; they may break into small fragments, or into massive blocks as thick as five feet. Generally the massive, thick beds are more common in the lower part of the group. The Prairie du Chien commonly caps bluffs along the St. Croix, Minnesota, and Mississippi rivers and their tributaries. It also underlies terraces and ridges adjacent to the major rivers, particularly the terraces along the Minnesota River between Burnsville and Chaska and the low ridges north of the Cannon River in southern Dakota County (Figs. 1 and 7).

The rocks of the Prairie du Chien Group are formed from sediments that were deposited in a laterally extensive, shallow sea, in which conditions did not vary much at any one time. Consequently, the physical characteristics of laterally equivalent rock layers are fairly uniform from one place to another within the Twin Cities basin. However, there are wide variations from layer to layer in the suitability of the rock for construction aggregate. Because of a lack of site-specific information in areas without outcrops or quarrying operations, covered areas where the bedrock may have better properties cannot be distinguished from covered areas where the rock has inferior properties. Therefore the Prairie du Chien is treated as a homogeneous entity across the region for the resource tonnage estimates.

The position of the water table in rocks of the Prairie du Chien Group is not treated quantitatively in this report because (1) it is quite irregular, and (2) an analysis of it would require the acquisition and interpretation of abundant site-specific hydrological data, an effort that is beyond the scope and purpose of this study. Nonetheless, some general comments about the level of the water in the bedrock can be made. Water entering the rock at topographically high sites such as bluffs, ridges, and plateaus is typically discharged rapidly into adjacent rivers and gullies along solution-enlarged fractures and bedding planes. This leaves the topographically high parts of the Prairie du Chien Group dry. Major exceptions to this general rule are the low-lying bedrock river terraces in northern Scott County and southwestern Washington County where the level of water in the bedrock is commonly just slightly above the elevation of the adjacent rivers. Depending on local conditions, the shallow water table may or may not present operational difficulties or environmental concerns.

Quarries

Although limestone and dolostone have been quarried from both the Platteville Formation and the Prairie du Chien Group for more than 120 years, all currently active quarries in the seven-county metropolitan area are in the Prairie du Chien Group. The rock is extracted by drilling and blasting, and is then loaded by power shovel, crushed, screened for proper size, and stockpiled or shipped. The aggregate is transported off-site by truck, rail, and river barge. A small proportion of quarry output consists of large blocks for rip-rap.

At the present time, no operating quarries are working more than a 50-foot thickness of the Prairie du Chien Group. Because the total thickness of potentially usable dolostone exceeds 250 feet in places, the possibility exists that larger and deeper quarrying operations may be proposed in the future. The locations of known active and inactive Prairie du Chien quarries are shown on the aggregate resources maps (Meyer and Mossler, 1999). Former Platteville Formation quarries are not shown on these maps.

Types of Data Used in Bedrock Mapping

Four general categories of information were used for geologic mapping of the dolostone bedrock.

1. Previously prepared maps that show the distribution and areal extent of bedrock outcrops. These include maps prepared for various Minnesota Geological Survey field studies, as well as maps prepared for University of Minnesota graduate theses. Particularly valuable was the earlier aggregate report by Meyer and Jirsa (1984), and unpublished outcrop maps prepared by Mossler (unpublished data). The archived maps were field-checked and upgraded as necessary.

2. Water-well and soils-borings data that had been interpreted for previous Minnesota Geological Survey studies, as well as newer water-well data interpreted specifically for this project. These data were augmented locally by Giddings soil-auger borings that targeted areas of sparse drilling and inferred shallow bedrock.

3. Soils maps published by the U.S. Natural Resources Conservation Service. These maps indicate, on the basis of generic soil classification, where carbonate bedrock is inferred to lie at depths of 60 inches or less.

4. Topographic maps published by the U. S. Geological Survey, which show the distribution of bluffs, flat plateaus, and ridges. In this part of Minnesota, these landforms are typically underlain by dolostone, limestone or other well-indurated sedimentary rock. The type of bedrock underlying a landform may be inferred from soil units on soil maps, bedrock outcrops, or soil borings and water-well records. In the absence of independent evidence for the underlying rock type, the landform itself gives some indication of the extent of shallow bedrock.

Deposit Classification for Bedrock Aggregate Resources

Areas where bedrock of the Prairie du Chien Group is 10 feet or greater in thickness and within 10 feet of the land surface are considered to contain potential aggregate resources for the purposes of this inventory. However, all areas where Prairie du Chien bedrock is less than 10 feet below the land surface, regardless of formation thickness, are shown on the geologic maps (Meyer and Mossler, 1999). Areas where the Prairie du Chien is less than 10 feet thick are not included in the resource-inventory calculations.

Each area shown on the map is classified to indicate the thickness range of the dolostone present and the reliability of information used to delineate it. Formation thickness is subdivided into three categories: (1) Dolostone thicker than 30 feet, (2) Dolostone ranges from 10 to 30 feet thick, and (3) Dolostone is less than 10 feet thick. The reliability of the map information is based on the number of data sets that were used (a) to delineate areas where the Prairie du Chien Group is present within 10 feet of the land surface and (b) to determine the geological attributes of the rock. This classification system is an approximate measure of the probability that the characteristics mapped (formation type, thickness, and depth to bedrock) are truly valid.

Excellent reliability indicates that outcrop data and data from water well borings or soil borings were used for mapping, in addition to data from soils and topographic maps. The distribution of well or outcrop data is fairly dense across an area for which the reliability is classed as excellent.

Good reliability indicates that either outcrop data or drilling data (water wells plus soil borings) were used, but not both. There are fewer outcrops or drilling data, and their distribution is not as uniform compared to the excellent category.

Fair reliability indicates that the mapping is based mainly on soil maps and land-surface topography. There are no outcrops, and only a few water-well or soils-borings records to support the inferences made. No areas of bedrock were mapped on the basis of only soils or only topographic information, i.e., on only one indirect line of evidence.

Descriptions of the potential resource areas for dolostone bedrock aggregate are presented in Appendix B. The descriptions are organized by county.

Estimating the Original Endowment—Bedrock Aggregate Resources

The procedure used to calculate bedrock-aggregate volumes and tonnages follows the general steps already explained for natural aggregates. For the volume calculations, we assign an arbitrary average thickness of 20 feet to deposits mapped as 10 to 30 feet thick. For deposits mapped as thicker than 30 feet (encompassing a possible thickness range of 30 to 280 feet), we assign an arbitrary thickness of 50 feet. This corresponds to the maximum height of working faces in current quarry operations and is therefore viewed as a practical value for resource estimation. It is substantially below the average thickness of the Prairie du Chien dolostone in much of the seven-county metropolitan area, however, and therefore leads to a conservative estimate of the dolostone volume potentially available for quarrying. Rock volumes (cubic yards) were converted to tons by assuming an in-place bulk density of 2.0 tons per cubic yard. A wastage factor of 25% was also applied.

Based on the definitions, protocols, and methods outlined above, we conclude that the seven-county metropolitan area contained about 2.5 billion tons of potential dolostone aggregate prior to European settlement and the beginning of urban development (Fig. 3, Table 3). This figure depends heavily on the formation thicknesses chosen for volume calculations, and also on the assumption (valid today) that rock covered by more than 10 feet of non-marketable overburden cannot be economically exploited.

The reliability-of-data categories shown on the geologic maps and discussed above were not factored into the bedrock tonnage calculations. That is, all areas mapped as having dolostone thicker than 10 feet and less than 10 feet below the ground surface were included in the calculations, regardless of whether the data supporting those mapping parameters were of fair, good, or excellent reliability. Users may wish to incorporate the reliability ratings in alternative resource estimates.

Total Resource Base

The total pre-settlement geological endowment of bedrock aggregate and natural aggregate resources in the seven-county metropolitan area was approximately 5.7 billion tons. Of this, about 2.5 billion tons was exploitable dolostone and 3.2 billion tons was exploitable sand and gravel. These are the starting quantities used to estimate the current resource base and probable future depletion dates, as developed in Part III of this report.

PART III — URBANIZATION AND ITS IMPACTS ON AGGREGATE AVAILABILITY

Background

Although geological processes have left large deposits of sand and gravel and extensive quantities of dolostone suitable for crushing, not all of these materials can be used or extracted economically as construction aggregates. Deposit thickness, amount of unusable material atop the sand and gravel deposits or bedrock, quality of the material, and position relative to groundwater are some of the factors that determine whether a deposit is suitable for mining. Additional prerequisites include access to a 9-ton road and a minimum land parcel size. Table 4 lists the criteria used by the aggregate industry to determine the suitability of a deposit for mining.

As discussed in Part II of this report, the location of natural aggregate (sand and gravel) and bedrock aggregate (dolostone) that meet industry's geologic requirements for construction aggregate have been delineated, and their geographic position and characteristics stored in a geographic information system format (Meyer and Mossler, 1999), that is also available as a paper map. This information was used to calculate the amount of resources originally available prior to 1840, when Europeans first settled the Twin Cities metropolitan area and began the urbanization process. At that time 5.7 billion tons of aggregate were available. Table 5 summarizes the amount (in tons) of aggregate material that were available prior to European settlement. The quantities listed are for resources that would meet the aggregate industry's standards or prerequisites. The extent of natural aggregate (sand and gravel) and bedrock aggregate (dolostone) resources prior to urbanization is shown in Figure 8. The sand and gravel deposits are divided into those that meet current industry standards, and those that do not. The bedrock resources shown are Prairie du Chien dolostone that could be quarried under today's economic conditions (i.e. covered by less than 10 feet of overburden). It does not, however show urbanization, environmental or zoning constraints.

Table 4. Factors used to determine the economic viability of aggregate deposits

Aggregate Resource Type	Factors used to determine economic viability
Sand and Gravel	At least 20 percent of bulk material is retained on number 4 sieve Thickness of cover material (overburden) is less than 10 feet Water table is deeper than 20 feet below the land surface Thickness of sand and gravel deposit is at least 20 feet Parcel size is at least 80 acres, preferably 160 acres Access to 9-ton road
Dolostone	Thickness of bed is at least 20 feet average Thickness of cover material (overburden) is less than 10 feet Dimensional stability—includes hardness, tensile strength, and minimal fractures and bedding planes Parcel size at least 80 acres Access to 9-ton road

Metropolitan Area Land Use, Housing and Demographics

Land Use

The seven-county metropolitan area covers approximately 2,975 square miles, of which about 175 are lakes and streams. Since 1838, when the first Europeans settled in what is now St. Paul, urbanization has steadily reduced the amount of open land. Urbanization has also proceeded on land that is rich in aggregate, and has encumbered those aggregate deposits before the resource could be utilized. Figure 2 (p. 3) shows the extent of urbanization in 1997 (Metropolitan Council, 1997 generalized land use, unpublished digital data), and the remaining (unencumbered) aggregate resources. By 1997, 35 percent of the land area of the region was urban. The acreage of land in urban use will increase by 35 percent between 1997 and 2020, and by another 20 percent between 2020 and 2040. Table 6 provides figures on characteristics of the metropolitan area.

Table 5. Calculated tonnage of original aggregate resources (geological endowment) based on deposit dimensions

Resource Group	Assigned deposit thickness*	Total tonnage for all land parcels	Tonnage for parcels 80 acres or greater	Tonnage for parcels 160 acres or greater
Sand & Gravel	40 feet † §	97,000,000	97,000,000	97,000,000
	20 feet	3,128,000,000	3,056,000,000	2,792,000,000
Total Sand & Gravel		**3,225,000,000**	**3,153,000,000**	**2,889,000,000**
Dolostone	50 feet	2,449,000,000	1,832,000,000	1,457,000,000
	20 feet	57,000,000	29,000,000	29,000,000
Total Dolostone		**2,506,000,000**	**1,861,000,000**	**1,486,000,000**
Total Aggregate		**5,731,000,000**	**5,014,000,000**	**4,375,000,000**

* Thicknesses assigned for resource calculations. See text, pp. 16 and 22 for detailed discussion.
† Since these beds are totally surrounded by other sand and gravel deposits, parcel size was not a constraint.
§ Mapped deposits in the 40-foot thickness category are all >160 acres, and are surrounded by deposits of lesser thickness.

Population, Employment and Housing

Since 1838 the seven-county metropolitan area has seen a steady increase in population. In 1997, the population was estimated to be just over 2.5 million. Population and employment are projected to increase by 23 percent and 25 percent, respectively, between 1997 and 2020, and by 40 percent and 28 percent, respectively, between 1997 and 2040. The number of new homes is projected to increase by 30 percent and 48 percent, respectively, in the same periods. Table 7 summarizes changes in population, housing and employment numbers through 2040.

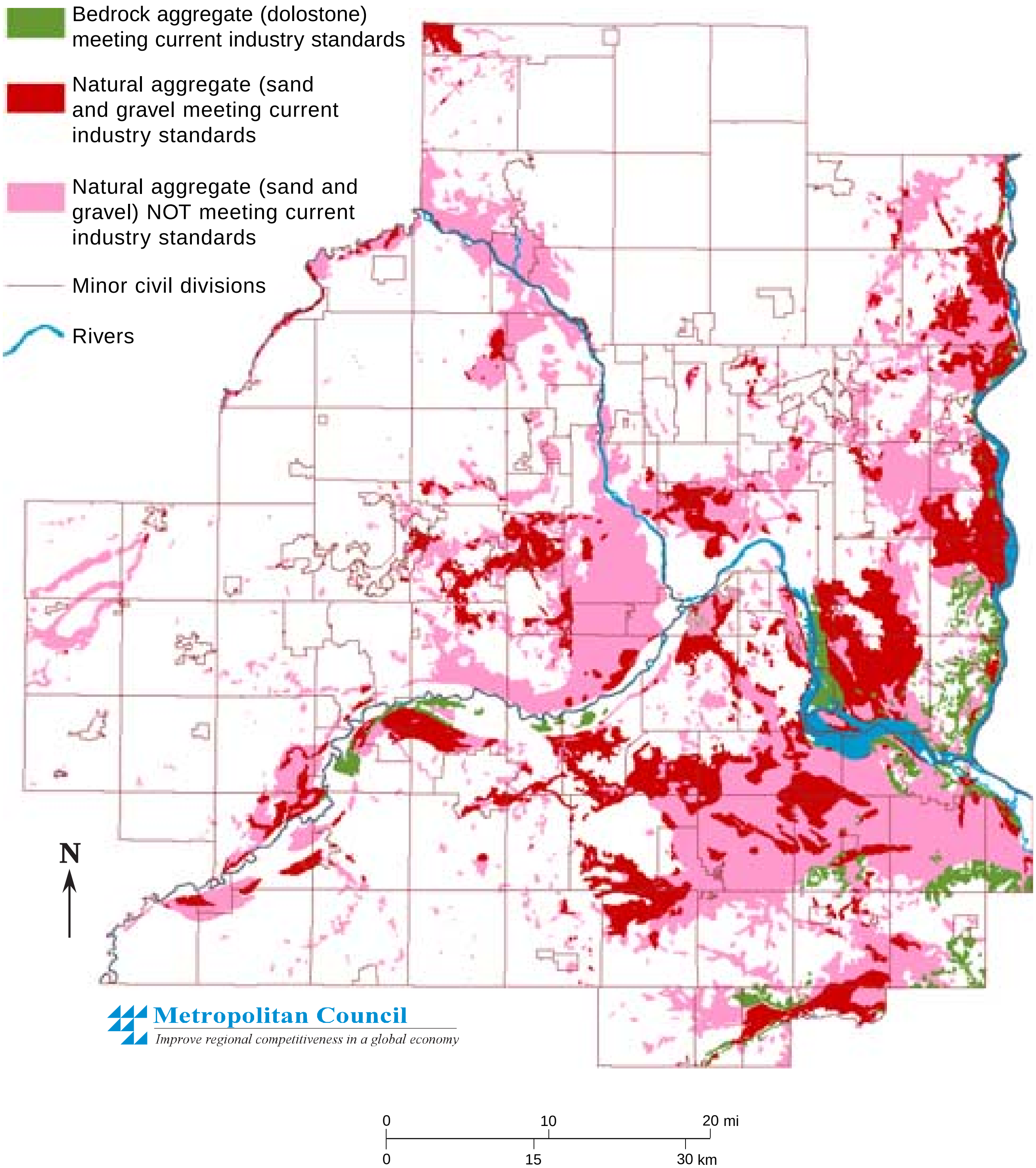


Figure 8. Map showing the distribution of aggregate materials in the seven-county metropolitan area, as modified from Meyer and Mossler (1999). This is a plan view of the pre-urbanization resource base, or the geological endowment.

Rate of Use of Aggregate Resources in the Seven-County Metropolitan Area

Historical Demand for Aggregate

Obtaining a true picture of the amount of aggregate used in the seven-county metropolitan area is a difficult task. Prior to the demise of the U.S. Bureau of Mines, that agency collected and published a variety of data on aggregate resources or usage. In recent years, the U.S. Geological Survey (USGS) has published *Mineral Industry Surveys*, which is an annual report that contains information on aggregate production nationwide, and on a state-by-state basis, and includes information formerly published by the Bureau of Mines. Unfortunately, because of the reluctance of some producers to provide the data requested, the production statistics reported by the USGS substantially understate the actual volume of aggregate produced. The 1998 annual estimate shows that in 1997 about 15.9 million metric tons (17.5 million short tons or tons) of aggregate were sold or used in the seven-county metropolitan area.

Table 6. Acreage of urban and non-urban lands (measured and projected) over the period 1980–2040

	1980*	1990*	1997†	2020§	2040§
Urban	470,000	549,000	622,000	841,000	1,001,000
Lakes & Streams	111,000	111,000	111,000	111,000	111,000
Non-urban	1,322,000	1,243,000	1,170,000	1,062,000	791,000
Total	**1,903,000**	**1,903,000**	**1,903,000**	**1,903,000**	**1,903,000**

* Metropolitan Council, 1995, 1990 land-use profiles, acreage summaries and maps by community
† Metropolitan Council, Community Development Division, GIS Section, 1997 generalized land-use (unpublished electronic data)
§ Metropolitan Council, Community Development Division, GIS Section, Growth Management Policy Areas (unpublished electronic data)

Table 7. Population, employment, and housing statistics (measured and projected) over the period 1980–2040.

[employment is the number of full-time-equivalent workers; housing is the total number of dwelling units]

	1980	1997	2000	2020	2040
Population * † §	1,986,000	2,515,000	2,586,000	3,100,000	3,512,000
Employment ¶ •	1,080,000	1,446,000	1,527,000	1,808,000	1,850,000
Housing * † §	750,000	972,000	1,005,000	1,265,000	1,443,000

* Metropolitan Council, 1993, An overview of historical population and housing trends in the Twin Cities metropolitan area
† Metropolitan Council, 1999, Population and household estimates, April 1 1988, for the Twin Cities metropolitan area
§ Metropolitan Council, 1996, Final Household and population forecasts 2000–2050
¶ Metropolitan Council, 1998, Interim Forecasts of population, households and Employment, Twin Cities metropolitan area, April 1998 (revised)
• Metropolitan Council, 1998, 1977 Employment by City/Township, Twin Cities metropolitan area

Annual reports produced by the Minnesota Department of Revenue's Minerals Tax Office are another source of information (Minnesota Department of Revenue, 1997, 1998, and 2000, unpublished data). Since 1983, Minnesota counties have been authorized to collect a tax of $0.07 per short ton on the removal of aggregate material in their jurisdiction (Minnesota Statutes, Section 298.75). This tax is collected by six of the seven metropolitan counties. Anoka County does not collect this tax. The Minerals Tax Office reports for 1998 and 1999 show that in 1997 and 1998 taxes were collected in the six metropolitan counties on about 24.1 and 23.9 million tons of aggregate resources. Of course, the aggregate extracted in these six counties is not necessarily all used in the seven-county metropolitan area. Moreover, since 1970 an increasing amount of material has been imported from Sherburne, Wright and Pierce counties into the seven-county metropolitan area, the exact amount of which is not known. When estimates of the aggregate production in Anoka County and the amount of aggregate imported from Sherburne, Wright and Pierce counties are incorporated in calculations, the total amount of aggregate used in the seven-county metropolitan area was 27 million tons in 1998.

According to a 1983 Metropolitan Council report *Aggregate Resources in the Twin Cities metropolitan area* (Schenk and Jouseau, 1983), the region consumed only 3.6 million tons of aggregate in 1950. With the housing market boom of the sixties and early seventies and the interstate highway system expansion, the annual consumption reached 17 million tons in the early 1970's. In 1980 the economic recession began to affect the construction market, and that translated into a lowering of the demand to 13 million tons in 1980. The steady increase in population and surging of the economy during the 1990's translated into a strong increase in the demand for aggregate, with demand reaching 27 million tons in 1997 and 1998 (Table 8).

Table 8. Aggregate demand and population for the seven-county metropolitan area, 1950–1998

[data are from the four sources listed in footnotes]

Year	Population	Aggregate Demand (in tons)
1950	1,185,694	3,639,000
1960	1,525,297	8,010,000
1965	1,735,991	13,237,000
1970	1,874,612	14,649,000
1975	1,934,554	12,855,000
1980	1,987,046	12,713,000
1990	2,288,729	20,926,000
1991	2,318,532	18,217,000
1992	2,352,121	19,683,000
1993	2,383,725	20,843,000
1994	2,415,207	23,888,000
1995	2,448,967	22,432,000
1996	2,482,858	24,315,000
1997	2,515,119	27,605,000
1998	2,544,353	27,005,000

Bureau of the Census, United States census of population 1950, 1960, 1970
Metropolitan Council, 1997, Adjusted population estimates 1980–1996
Metropolitan Council, 1999, Population and household estimates for the Twin Cities metropolitan area, April 1998
Twin Cities Metropolitan Planning Commission, The Joint Program, Metropolitan Population Study, Planning Report (undated)

Future Demand for Aggregate

Forecasting future demand for aggregate is a task filled with uncertainties. In this case, forecasting is even more tenuous because there are no solid figures on which to base an historical trend. As shown in the previous section, figures for the historical demand for aggregate are only approximations; uncertainties derive from under-reporting of production, and a lack of data on the amounts of aggregate imported into or exported from the seven-county metropolitan area.

Several variables were evaluated to determine their usefulness in forecasting future demand for aggregate. These variables included population, number of households, building permits issued, dollar value of residential construction, infrastructure (roads and utilities), non-residential construction and total construction. Data on annual construction costs for 1990–1998 are given in Table 9.

Table 9. Dollar cost of construction in the seven-county metropolitan area, 1990–1998.
[Data from Metropolitan Council, 1999, Major New Residential Projects in the Twin Cities metropolitan area]

Year	Total Construction	Residential Construction	Non-Residential Construction	Infrastructure Construction
1990	3,247,239,000	1,434,003,000	1,425,428,000	387,808,000
1991	2,752,438,000	1,451,255,000	957,394,000	343,789,000
1992	3,136,839,000	1,806,403,000	947,610,000	382,826,000
1993	3,140,079,000	1,973,871,000	765,658,000	400,550,000
1994	3,481,667,000	1,724,624,000	1,305,084,000	451,959,000
1995	3,412,017,000	1,469,139,000	1,460,784,000	482,094,000
1996	3,365,580,000	1,694,178,000	1,227,287,000	444,115,000
1997	3,841,100,000	1,604,176,000	1,624,548,000	612,376,000
1998	4,807,715,000	2,095,543,000	2,145,274,000	566,898,000

These variables correlate to varied degrees with aggregate demand, as measured by standard statistical techniques. The strongest correlations are shown in Figures 9–12. Aggregate demand correlates best with population (Fig. 12), which is the only variable for which historical data and long-term forecasts are readily available. This is important in attempting to forecast aggregate use for 20 and 40 years into the future.

Two trends are apparent on the graph of aggregate demand vs. population (Fig. 12) — one for the entire 1950–1998 period, and one for the period 1990–98. Both lines demonstrate a very good fit; the 1950–98 line has a R^2 value of 0.93 while the 1990–98 line has an R^2 value of 0.82. The slope of the line for the 1990–98 period is much steeper and shows an increased per capita use of aggregate. One could ascribe this increase to a number of causes; unfortunately no data are readily available to explain the trend. The most likely causes include the strong economy and expansion of businesses that resulted in a boom in office building during the 1990–1998 period.

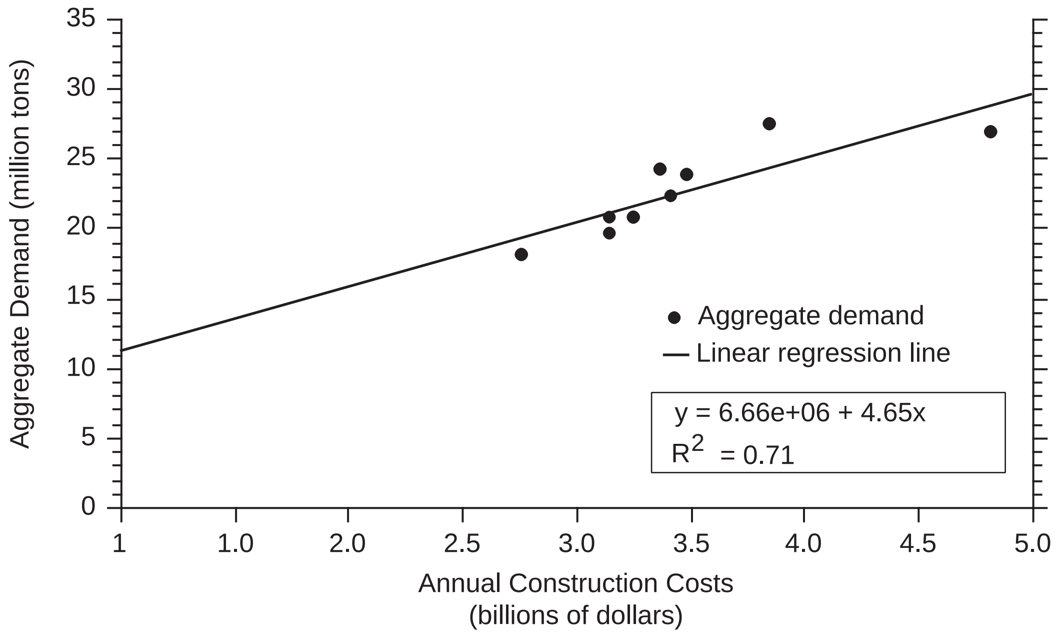


Figure 9. Aggregate demand vs. total annual construction costs in the seven-county metropolitan area for 1990–1998.

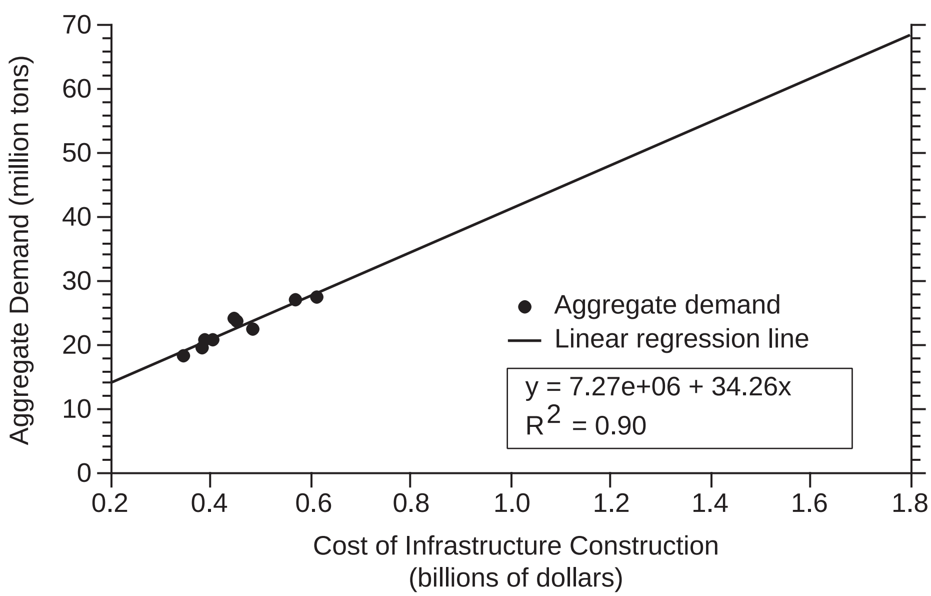


Figure 10. Aggregate demand vs. infrastructure construction costs in the seven-county metropolitan area for 1990–1998.

The linear regression equations shown in Figure 12 were used to forecast the annual demand for aggregate through year 2040. Because of the change in the per capita demand in the period 1990-98, it was determined that the forecast should use both the long-term (1950-1998) equation as well as the short-term (1990-1998) equation. The result is a range of forecasts. The use of the long-term (1950–1998) equation predicts an annual demand of 41 million tons of aggregate in 2040. This translates to a demand of over 1.4 billion tons of aggregate in the seven-county metropolitan area between 2000 and 2040. The short-term (1990-1998) equation predicts an annual aggregate demand of 58 million tons by 2040, which translates to a demand of over 1.8 billion tons between 2000 and 2040.

A 1999 industry report (*Draft EIS: Lakeland Sand and Gravel Mine Expansion and Reclamation Plans,* Washington County Planning, 1999) states that the annual demand for aggregate in the seven-county metropolitan area reached 32 million tons in 1998, and is increasing at the rate of 100,000 tons a year. The report further states that demand will reach 40 million tons annually in 2040. On the basis of these figures, the seven-county metropolitan area will need about 1.5 billion tons of aggregate during this 40-year period. Those numbers are in line with the figures of 1.4 and 1.8 billion tons developed during the present study.

Impact of Urbanization on theAvailability ofAggr egate Deposits

Urbanization of the seven-county metropolitan area generally takes place in accord with local comprehensive plans prepared as required by the 1976 Metropolitan Land Planning Act and subsequent amendments (Minnesota Statutes, Sections 473. 851 to 473. 866). Local comprehensive plans must be consistent with planned, orderly and staged development, and with the metropolitan system plans (Minnesota Statutes, Section 473.851). The law is silent on the need for comprehensive plans to address (1) the issue of planning for aggregate resources or (2) the protection of these resources for future use. Similarly, the Metropolitan Council plans contain no policies or directions on the need to preserve the resource for future use.

In the absence of policies or planning requirements for aggregate resources management, development of the seven-county metropolitan area has taken place without sufficient consideration for the location of aggregate resources and the preservation or conservation of these resources. Prior to urbanization, approximately 165,000 acres or 9.2 percent of the land area of the region contained aggregate deposits that would today meet the industry’s requirements for quality, thickness of deposit, amount of cover and distance to the water table. By 1997, almost 90,000 acres of those deposits had either been mined or encumbered by urbanization.

Urbanization also impacts the aggregate resources because it fragments the available deposits into pocket-sized sites, rendering them uneconomical to mine. This fragmentation of the aggregate resources by urban or suburban uses, means that the resources cannot be used. Figures 13 and 14 show the extent to which bedrock aggregate (dolostone) and natural aggregate (sand and gravel) resource sites have been fragmented. Dolostone bedrock was originally recorded at 356 sites, whereas in 1997 a total of 1,054 sites were recorded, of which only 34 were 80 acres or larger. Similarly, a total of 408 natural aggregate (sand and gravel) resource sites were originally present, but in 1997 the remaining resources were recorded at 3,549 sites, of which only 182 met the 80-acre minimum size, which is the minimum acreage required for an economically viable mining operation.

In its 1996 *Regional Blueprint* (Metropolitan Council, 1996), the Metropolitan Council provides sketches of the policy areas for its regional growth strategy. It depicts the 2000 Metropolitan Urban Service Area (MUSA) boundary, as well as illustrative boundaries for the 2020 MUSA and the

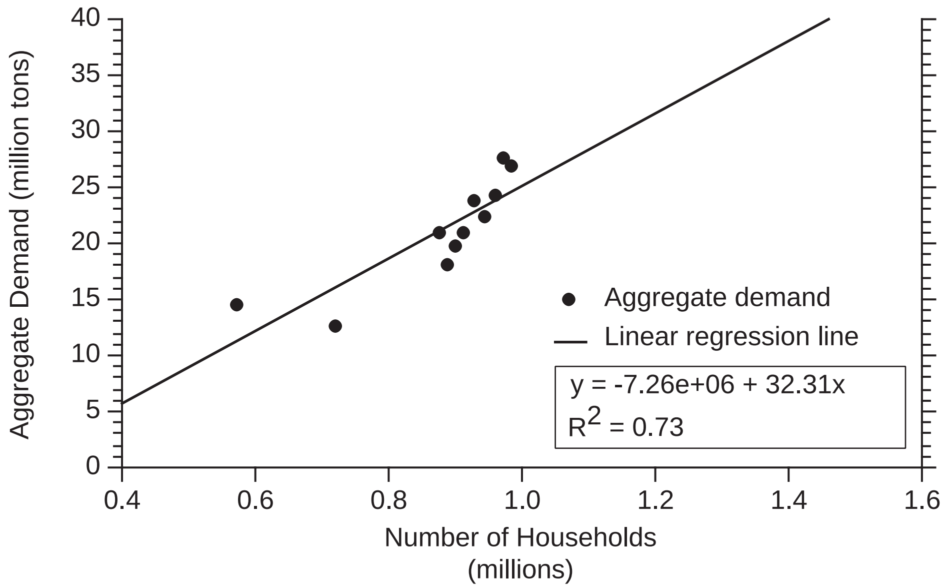


Figure 11. Aggregate demand vs. number of households in the seven-county metropolitan area for 1970–1998. Data from Metropolitan Council (1997, 1999).

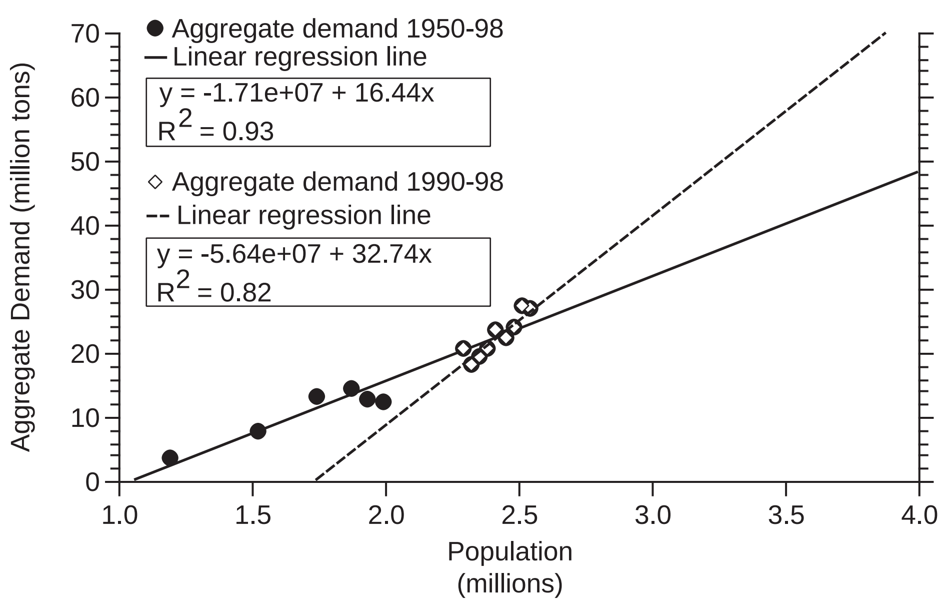


Figure 12. Aggregate demand vs. population in the seven-county metropolitan area for 1950–1998. Black dots with diamonds inside are for period 1990–1998; plain black dots are for period 1950–1989. Regression lines are fitted to the full (1950–1998) dataset (solid line) and to data for the years 1990-1998 (dashed line). Data from Metropolitan Council (1997, 1999).

2040 Urban Reserve. These are areas planned for future urbanization, with provisions for transportation and sewer infrastructures and other urban services. Approximately 380,000 acres will become urbanized between 1997 and 2040. Without appropriate planning to preserve the aggregate resources, or to ensure that the aggregate resources are extracted prior to urbanization, the seven-county metropolitan area will fail to use, or waste, approximately 316 million tons by 2020, and 582 million tons by 2040. Those losses will be solely the result of paving or building on top of the resources, or through urbanization fragmenting the deposits into parcels too small to be economically mined. These losses are equal to 35 percent of the resources that were still available to the region in 1997 in economically viable sites, or equivalent to 32 to 42 percent of the total demand for the next 40 years. Figures 15 and 16 show the extent of urbanization in years 2020 and 2040, and the aggregate resources that will remain unencumbered.

It is important to note that the present study did not examine the existing or planned zoning for areas that contain natural aggregate (sand and gravel) or bedrock aggregate (dolostone). Neither did this study examine the zoning laws that prevent mining, or assess the difficulties of obtaining any necessary zoning changes or obtaining the necessary mining permits. This means that substantial volumes of aggregate resources shown on the maps could be unavailable for extraction. Similarly, the study did not survey landowners to determine their interest in selling their land or the aggregate mineral rights to a mining company. Obviously, the unwillingness of property owners to allow for the extraction of aggregate would decrease the amount of aggregate available to the seven-county metropolitan area.

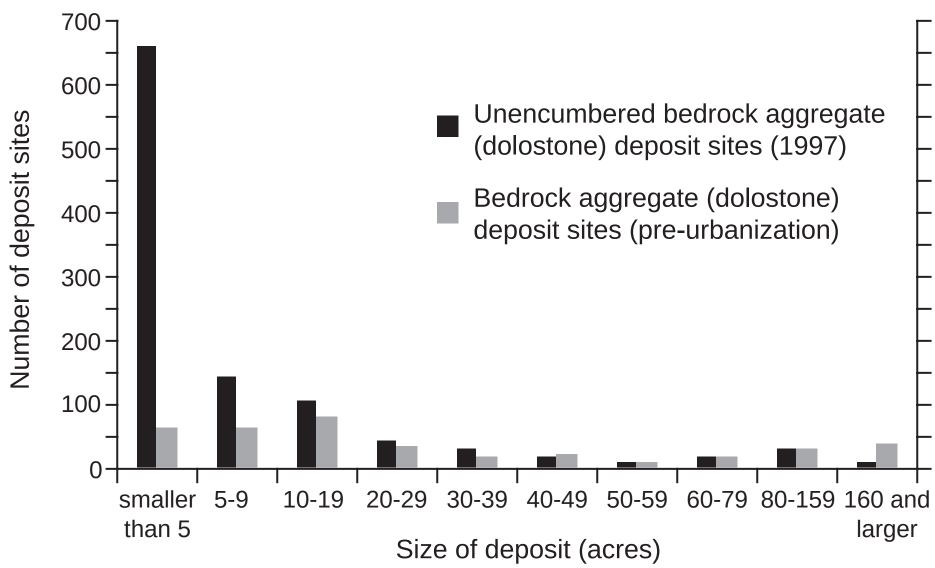


Figure 13. Number of sites at which potentially mineable dolostone is present, showing acreage (or parcel size) of deposit. Data are for (1) pre-urbanization dolostone sites and (2) dolostone sites unencumbered by alternative land uses in 1997. Note that the number of small land parcels (< 40 acres) has increased since European settlement, whereas the number of large land parcels (> 40 acres) has decreased. The greatest surge has been in the number of land parcels smaller than five acres.

Future of the Aggregate Resources

Although the quantity of aggregate resources depends fundamentally on the amount of geologically appropriate material originally present in the ground, it also depends on the amount already extracted, the amount not available because it has been paved over or physically encumbered in other ways, and the amount not available because of zoning and environmental regulations. Landowner's willingness to make the resource available is, of course, the ultimate test. This study has focused solely on the geologic and the urbanization factors. It does not take into consideration zoning or the landowners' willingness to sell, as these can be changed, albeit sometimes with great difficulty.

Analysis of the geological data, together with that of urbanization, environmental and economic constraints, leads to the conclusion that, in 1997, the remaining aggregate resources in the seven-county metropolitan area were about 1.7 billion tons. Natural aggregate (sand and gravel) resources were about 1.1 billion tons, whereas bedrock aggregate (dolostone) resources were estimated to be 0.6 billion tons.

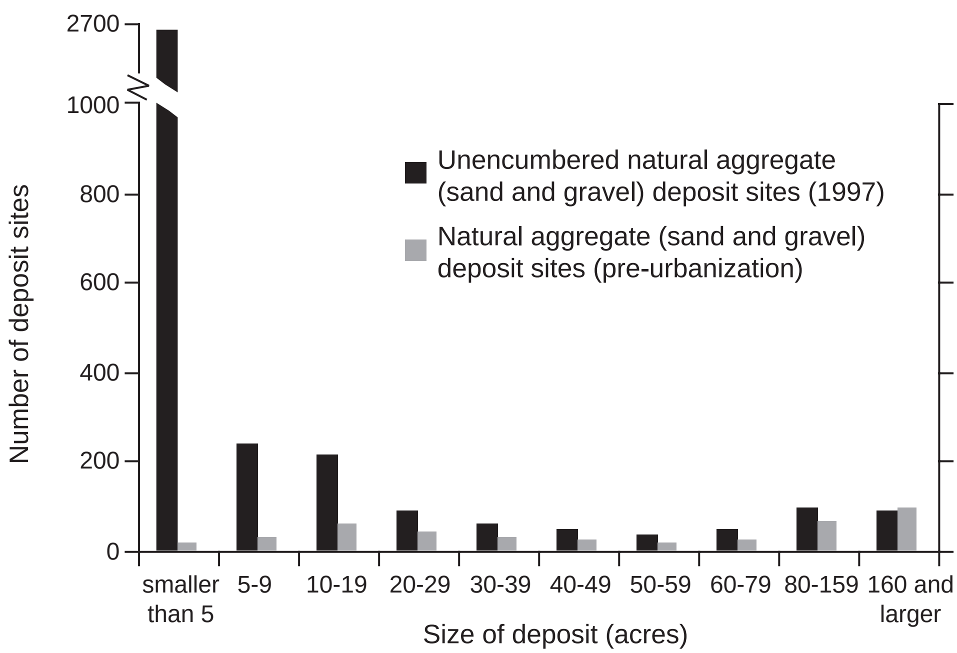


Figure 14. Number of sites at which potentially mineable sand and gravel are present, showing the acreage (or parcel size) of the deposit. Data are for (1) pre-urbanization natural aggregate sites and (2) natural aggregate sites unencumbered by alternative land uses in 1997. Note that the number of parcels of all sizes smaller than 160 acres have increased since European settlement. The greatest increase has been in the number of land parcels smaller than five acres.

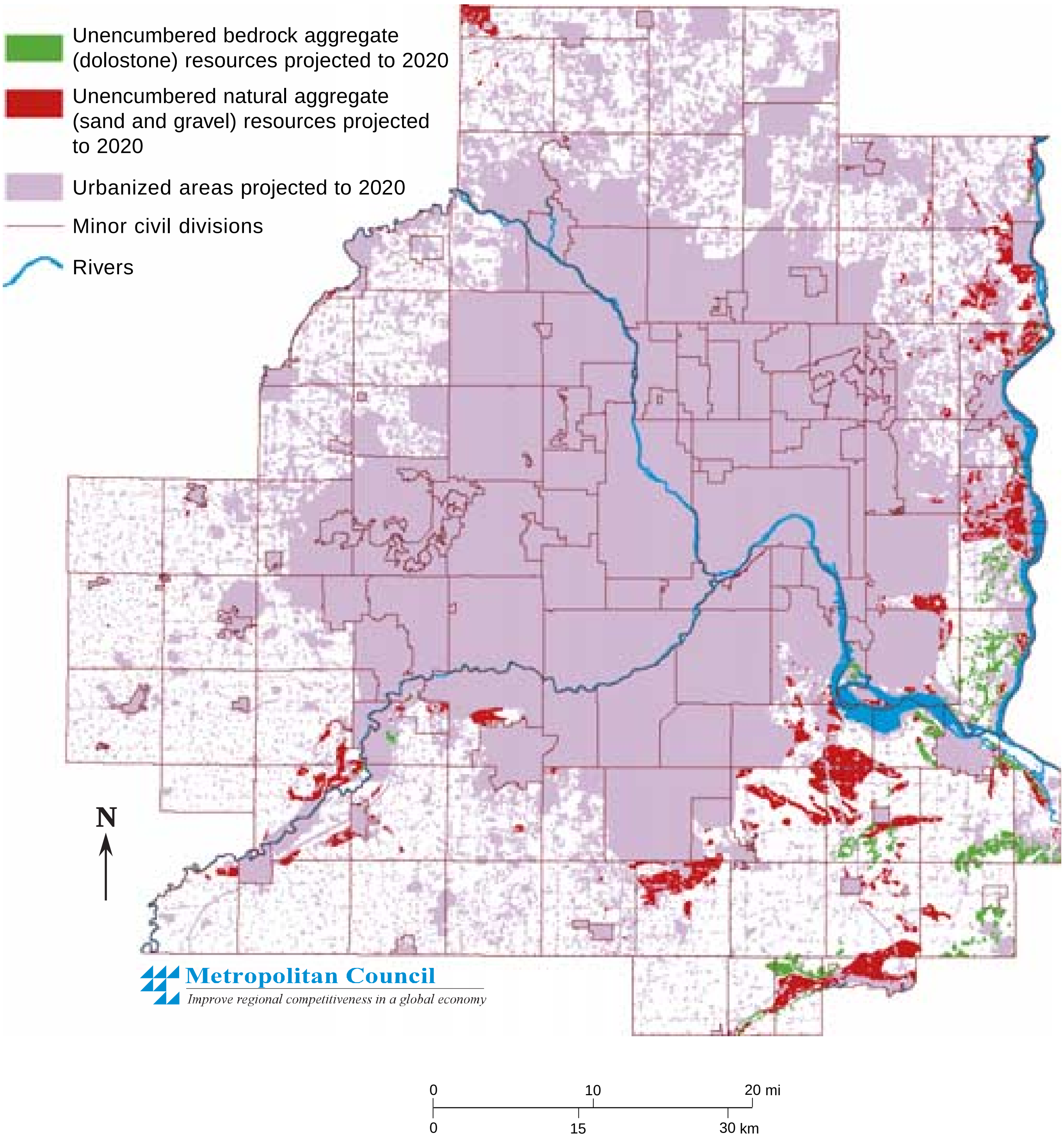


Figure 15. Map showing the projected extent of urbanized areas in 2020, and the aggregate-bearing lands that are projected to be unencumbered by alternative land uses in 2020.

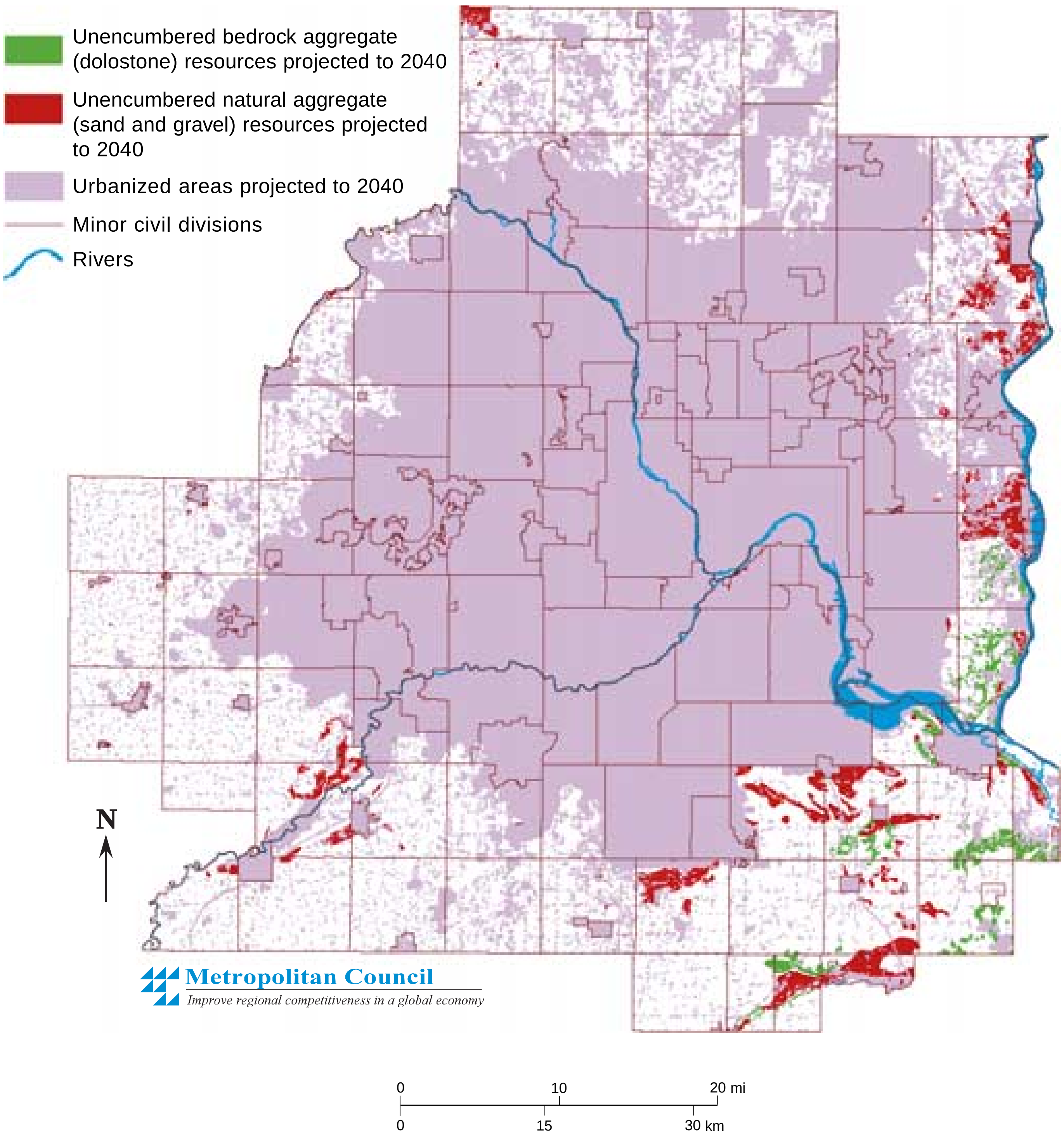


Figure 16. Map showing the projected extent of urbanized areas in 2040, and the aggregate-bearing lands that are projected to be unencumbered by alternative land uses in 2040.

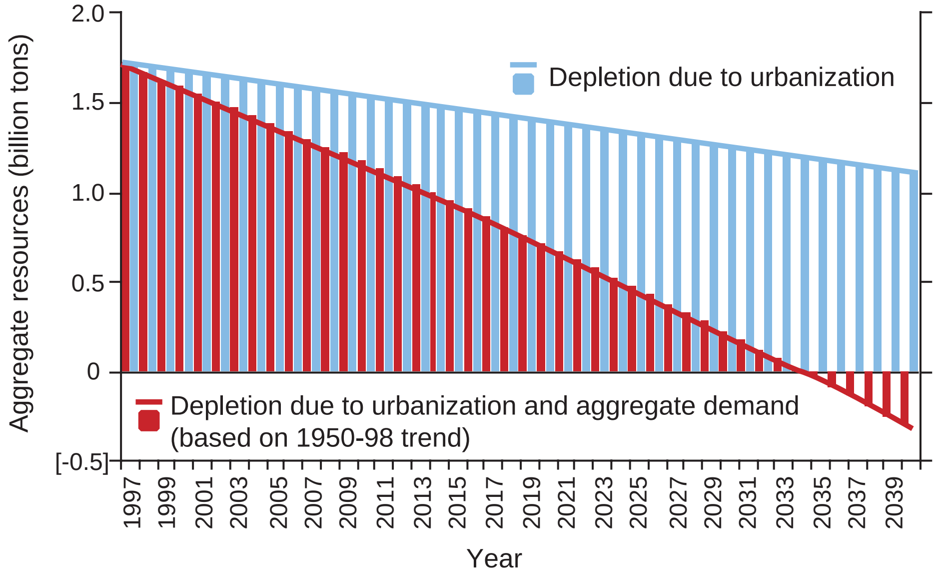


Figure 17. Depletion of the aggregate resource base for period 1997–2040. The blue curve shows depletion that will occur through loss of aggregate-bearing lands to urbanization; the red curve shows the total depletion stemming from land loss plus consumption of the resource as projected from the 1950–1998 use-rate scenario. This consumption model predicts the exhaustion of resources in 2034 (Appendix Table E–1).

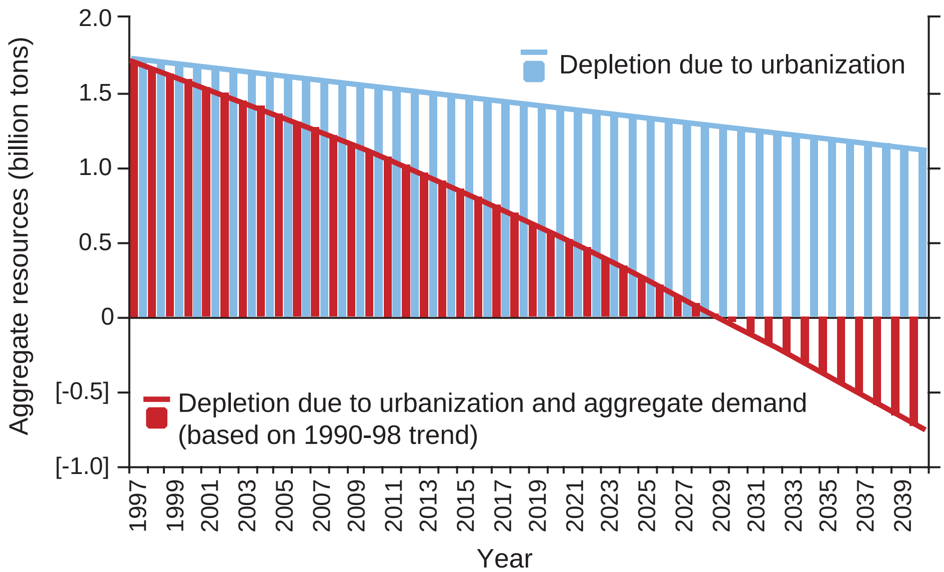


Figure 18. Depletion of the aggregate resource base for the period 1997–2040. The blue curve shows depletion that will occur through loss of aggregate-bearing lands to urbanization; the red curve shows the total depletion stemming from land loss plus consumption of the resource as projected from the 1990–1998 use-rate scenario. This consumption model predicts the exhaustion of resources by 2029 (Appendix Table E–1).

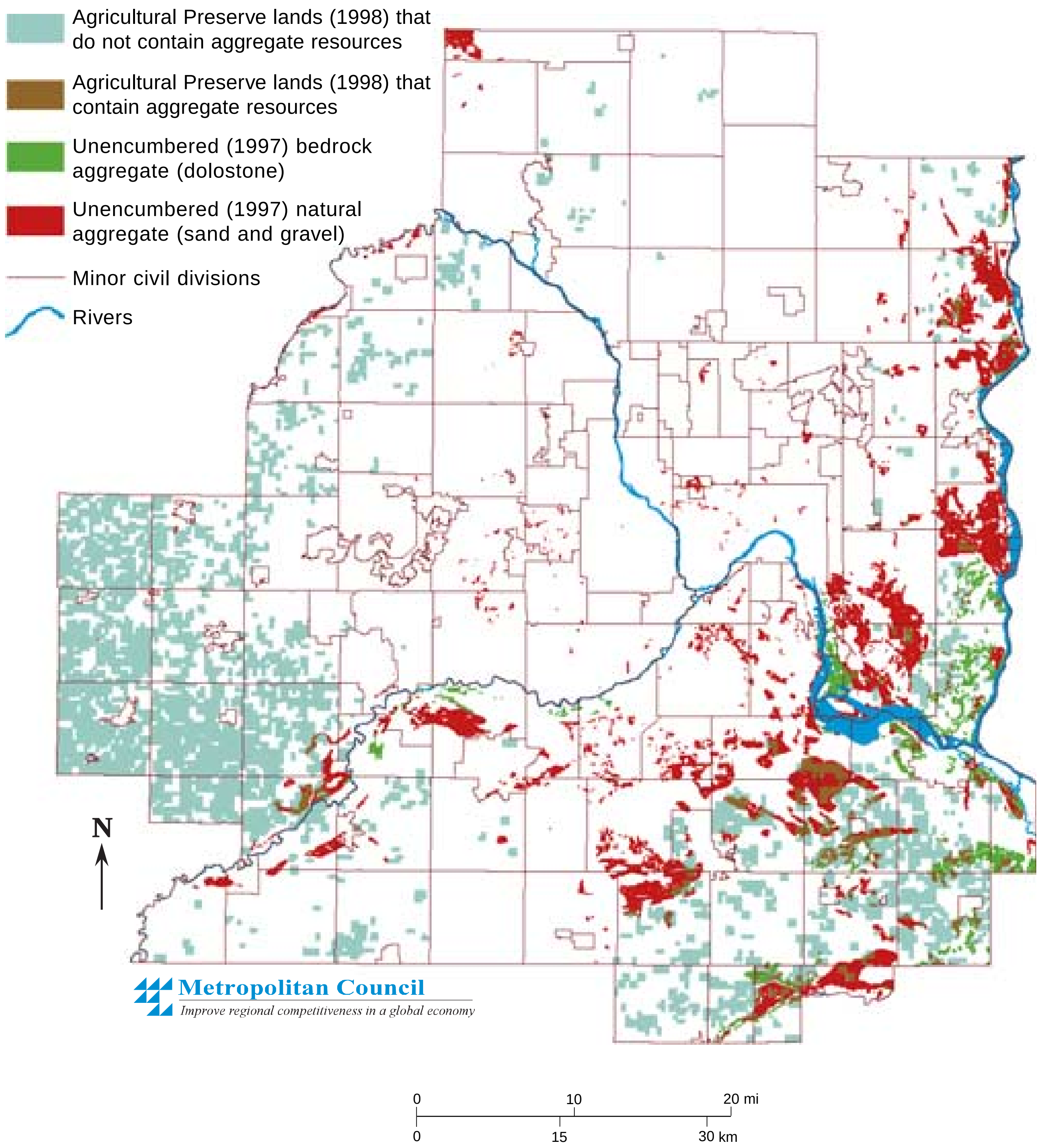


Figure 19. Map showing the distribution of lands designated as agricultural preserves. Note the impact of these exclusions on lands potentially available for aggregate mining.

Under the present growth management strategy scenario, and without government action to preserve existing resources or to ensure that the resources are extracted before the land is urbanized, 582 million tons of aggregate will be lost by 2040 through paving over of the resources, and from the fragmenting of economically viable sites into smaller parcels that can no longer be economically mined (Figs. 15 and 16). This will leave the region with only about 1.1 billion tons. The forecasted total aggregate demand for the period 2000 to 2040 suggests the need for 1.4 to 1.8 billion tons of material, depending on whether the 1950-98 (long term) demand trend or the 1990-98 (short-term) demand trend is used. The combined 40-year demand and loss to urbanization will use and encumber 2 billion to 2.4 billion tons of aggregate resource. The result is that the seven-county metropolitan area will see a shortage of aggregate prior to 2040.

Based on the assumptions about the amount of aggregate available to the region in 1997, the forecasted rates of use of aggregate, and the amount of aggregate that will be lost to the effects of urbanization, the seven-county metropolitan area will likely run out of resources between 2029 and 2034 (Figs. 17 and 18). The 2029–2034 range is the result of the two demand forecast scenarios. However, preservation of the deposits until the resources are needed, instead of covering them with urban development, could extend the availability of the resource to 2047.

Agricultural Land Preservation and Aggregate Resources

Since 1980, landowners in the seven-county metropolitan area have been able to enroll farmland in the Minnesota Agricultural Preserves Program to receive a number of benefits. Land so-enrolled is classified and assessed according to its agricultural value rather than its market value, and may not be included in public improvement projects. The lands enrolled in the Agricultural Preserves Program, as well as the farming practices in these areas, are also protected against prohibitive ordinances and regulations that restrict normal farm practices. Enrolled land is under a long-term restrictive covenant that can be removed only eight years after the decision not to continue with the Agricultural Preserves Program. In exchange for those benefits, land enrolled must remain in agricultural use.

The Metropolitan Council has been a strong supporter of agriculture and the preservation of farming as a way of life in the metropolitan area. The growth management strategies of the Council, as enunciated in the 1996 *Regional Blueprint* (Metropolitan Council, 1996), feature the long-term preservation of agricultural land as an important piece in providing for the orderly and economic development of the region. In 1999, approximately 192,000 acres were enrolled in the Agricultural Preserves Program (Metropolitan Council, 1999). Figure 19 depicts land enrolled in the Agricultural Preserves Program and the remaining aggregate deposits. Over 2,400 acres of bedrock aggregate (dolostone) and about 8,500 acres of natural aggregate (sand and gravel) are within areas that are enrolled in the Agricultural Preserves Program. These areas contain a total of about 495 million tons of bedrock and natural aggregate.

Mining and agriculture are not necessarily incompatible, because some aggregate-bearing land can be restored to provide for the return of farming on completion of the mining activities. If an owner were to withdraw land from the Agricultural Preserves Program with the intention of extracting aggregate, no mining could take place within eight years of the date on which the notice of withdrawal was filed. Moreover, mining would have to comply with all applicable zoning and environmental regulations. Long-term enrollment of aggregate-bearing farmland in the Agricultural Preserves Program could move the date of the aggregate shortage forward by 10–12 years to around 2016–2018.

Conclusions

The 1999 study of aggregate resources of the seven-county metropolitan area was jointly undertaken by the Metropolitan Council and the Minnesota Geological Survey. The study provides an historical perspective and an indication of the demand for aggregate and the future of aggregate resources in the seven-county metropolitan area.

1. The seven-county metropolitan area contained over 5.7 billion tons of aggregate resources when Europeans first settled in the area in about 1840. Within the following 160 years, the available aggregate resources have been reduced by 70 percent to 1.7 billion tons.
2. Demand for aggregate has steadily increased over the years, from about 7.5 tons per capita per year in the mid-1960's, to 9.1 tons per capita in 1990, and to about 11 tons per capita per year in 1997.
3. Future demand for aggregate is forecasted to grow to 16.7 tons per capita in 2040, using a scenario that reflects the buoyant economic growth of 1990–98 growth period, or to 12 tons per capita using the 1950–98 growth scenario.
4. Total demand for aggregate during the 2000-2040 period will reach 1.4 billion to 1.8 billion tons.
5. The population growth and economic development of the region will lead to the urbanization of an additional 590 square miles between 2000 and 2040.
6. A continuation of the historical trend of urbanizing aggregate-bearing sites before extracting the aggregate resources will result in a loss of nearly 600 million tons of aggregate, or 35 percent of the remaining resources over the next 40 years.
7. The combined loss of aggregate due to urbanization, and the demand for aggregate will cause the seven-county metropolitan area to run out of aggregate resources as early as 2029, assuming the present growth trend.
8. Nearly 11,000 acres that contain about 495 million tons of aggregate resources are locked in sites enrolled in the Agricultural Preserves Program. This aggregate will not be available for another 8 years after the landowners have given notice that they no longer wish the land to be enrolled in the program. Long-term continuation of the enrollment could bring the shortage of aggregate forward by 10–12 years.
9. The lack of regional and local policies for management of aggregate resources has resulted and will continue to result in the loss of vast quantities of aggregate through paving over the material, fragmenting sites that contain aggregate, thus making them uneconomical to mine, as well as through land-use conflicts and zoning issues, unless appropriate measures are taken for orderly use of the resource.

APPENDICES

Geologic descriptions of aggregate deposits, organized by county, are presented in Appendices A (natural aggregate) and B (bedrock aggregate). Appendix C is a summary of physical and chemical test data on a small set of aggregate samples collected from surface excavations and test borings. Appendix D presents details of the methods used to quantify and project the geographic effects of urbanization. Appendix E presents details of the methods used to estimate the depletion of aggregate resources.

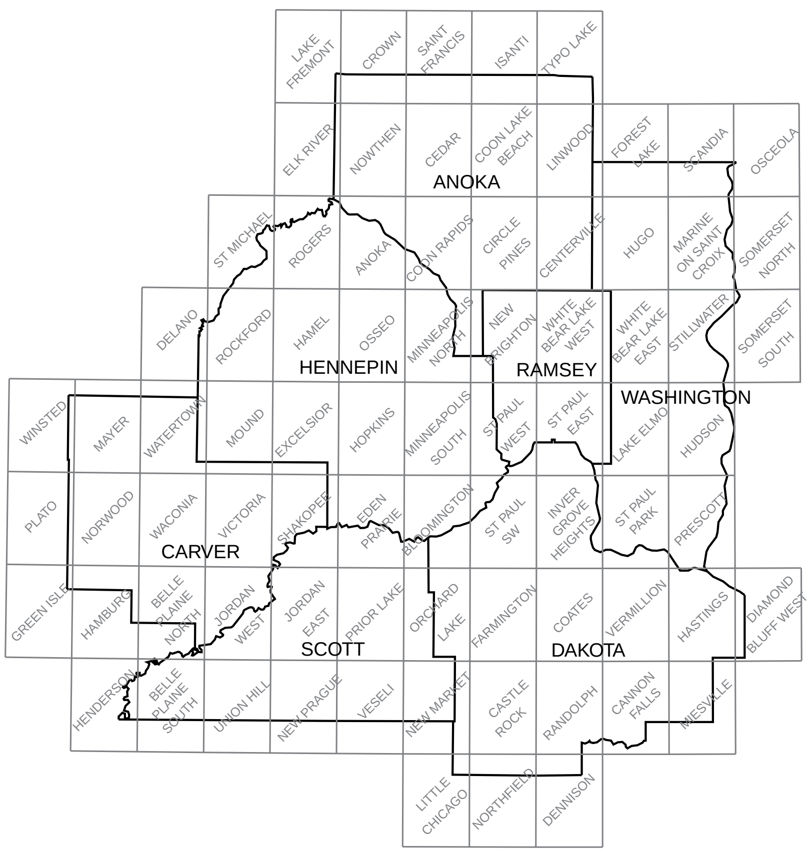
APPENDIX A

DESCRIPTION OF SAND AND GRAVEL (NATURAL AGGREGATE) DEPOSITS

In this appendix, the sand and gravel deposits are described alphabetically by county and informal deposit name. The distribution of these deposits is shown on the aggregate resources maps of Meyer and Mossler (1999). For further information on the location of cultural and geographic features identified in the text, the reader is directed to the relevant 7.5-minute topographic quadrangle (Appendix Figure A-1).

ANOKA COUNTY

The very large Anoka Sand Plain, which covers much of Anoka County, is not mapped as an aggregate resource despite its name. Generally, the near-surface sediment within the plain is fine to medium sand of very limited commercial value. In most places, at least 20 feet of sand overlies any potential gravel resources. In places where gravel beds are closer to the surface, they are overlain by more than 10 feet of sand and are commonly less than 10 feet thick. Rarely, the sand deposits contain small bodies of fine gravel that cannot be mapped with available data.



Appendix Figure A-1. Seven-county area showing location and names of 7.5-minute topographic quadrangle maps.

Burns Ice-Contact Deposits (BRI): Deposits laid down predominantly beneath the ice of the Superior lobe as it receded to the northeast. They were deposited mostly as long sinuous ridges (eskers) that trend west to southwest across the northwestern corner of the county. Shale clasts are present in places in the upper portion where the sediments have been reworked by Grantsburg sublobe meltwater. Although several gravel pits have been opened in this deposit, the gravel beds are "spotty", and intermingled with or covered by substantial amounts of sand and clay. Small but locally significant gravel deposits probably remain to be found.

Elk River Outwash (ERO): Material deposited near the margin of the retreating Superior lobe; related geologically to a gravel deposit north of Elk River in Sherburne County, which is being extensively mined at present. Due to the proximity of Superior-lobe ice at the time of deposition, the sand and gravel is commonly interbedded with till, especially near the deposit margins. The outwash was overridden by the Grantsburg sublobe, but the Grantsburg-deposited overburden is thin in most areas. Prospects for significant, high-quality gravel deposits within the Elk River outwash seem good, but gravel percent and deposit thickness are probably quite variable.

Grantsburg Ice-Contact Deposits (GBI): A group of minor accumulations of sand and gravel, some or all of which may actually be Superior-lobe deposits that were reworked or thinly buried by the Grantsburg sublobe. These deposits form small inclusions in clay-till moraines near Highway I-35E in southeastern Anoka County, and in the western part of Anoka County. Although it was not possible to map them, pockets of sand and gravel are probably also present along Ford Brook in Burns Township. None of these deposits is considered a very significant resource.

Langdon Terrace (LGT): Lower terrace along the Mississippi River north of Fort Snelling. In Anoka County, sediments of the Langdon terrace deposit generally consist of more than 10 feet of sand overlying gravel. Toward the river, gravel may be closer to the surface in places. Elsewhere, the deposit consists only of thick sand. Sediments of the Langdon terrace were not mapped in much of southern Anoka County because there they consist of fine sand or sandy glacial till. This deposit is probably not a significant gravel resource in Anoka County.

Mississippi Floodplain (MPF): Recent alluvium deposited by the Mississippi River. Access to mine these deposits is unlikely to be granted.

Richfield Terrace (RFT): The highest terrace along the Mississippi River. The Richfield terrace has been dissected by water and sculpted by wind, and merges into the Anoka sand plain. Sediments of the Richfield terrace consist of sand that blankets a variety of older deposits, thus making the terrace deposit, as a whole, difficult to map. Boundaries are based mostly on water-well logs, which are very subjective. Where mapped, the deposit consists of more than 10 feet of sand, which sometimes includes a small percentage of gravel, and overlies interbedded sand and gravel. Much of the terrace material was not mapped as a resource because it consists of predominantly thick, fine to medium sand, or thin sand that overlies till or clay. Borings from two pits at the southern end of Crooked Lake encountered mostly sand. One boring penetrated 18 feet of gravel, most of which was below the water table. The amount of spall material (material which causes "pop-out" in hardened concrete) above the water table is less than 1 percent (by weight), but below the water table in another pit the amount of spall is close to 2 percent. Several other pits have been worked in this deposit; none appears to have produced much gravel.

CARVER COUNTY

Sizable deposits of moderate- to poor-quality sand and gravel are present along the southeastern border of Carver County along the Minnesota River, and along the South Fork of the Crow River, which flows through the northwestern portion of Carver County.

Bluff Gravel (BLG): Sand and gravel deposits exposed along the steep slopes adjacent to the Minnesota River that are not included in other deposit categories. The bulk of the material is related to the Des Moines lobe. Most of these deposits consist of thick, gravel-poor sand or interbedded sand and clay, although some good gravel may be present locally.

Crow River Outwash (CWO): Several coalescing valley-train deposits parallel to the drainage of the present-day South Fork Crow River that were laid down during the melting of the Des Moines lobe. In Carver County, these deposits generally contain less than 20 feet of gravel, and the water table is less than 20 feet below surface. Irregular pockets of thicker gravel exist, and many have been mined.

Samples from pits in Camden Township south of New Germany average 3.5 to 4 percent spall with more than 3 percent shale. However, notes recorded for a pit in section 32 indicate 16 percent shale in material retained on the number 4 sieve. A pit in the southwest corner of section 16 was noted to have “good gravel grading up to 1-1/2 inches.” Pits just north of Mayer are typically opened in fine, sandy gravel, although pockets of coarser material exist. One pit was noted to have “considerable crushing in spots, but poor grading.” Another pit along a tributary in section 24, Hollywood Township, yielded samples that contain about 9 percent shale and total spall of about 10 percent. Pits south of Watertown are generally opened in sand and fine gravel, although in samples from a layer in the upper 3 to 6 feet, 7 to 20 percent of the gravel was retained on the 3-inch screen, including boulders that range from 8 to 12 inches in diameter. Although most of this deposit was given a classification of 4, enough gravel is available over a wide enough area to make it a resource of at least local significance.

Des Moines Ice-Contact Deposits (DEI): Small, scattered, deposits of modified sand and gravel associated with the ablation of the Des Moines lobe. Several of these deposits parallel present drainageways, such as those in Hollywood and Benton townships. These probably represent collapsed sediment of supraglacial meltwater streams. Generally, deposits included in this unit contain gravel beds thinner than 10 feet that are covered by more than 10 feet of overburden. These despoits are worked locally. Spall content is probably high.

Grey Cloud Terrace (GRT): Lower-level terrace along the Minnesota River. In Carver County, deposits of the Grey Cloud terrace are present in Chaska and Chanhassen townships, and in a small area south of Carver. Little subsurface information is available, but the geomorphology of the terrace suggests that some good gravel may be present. However, most of the deposit is not available for mining.

Langdon Terrace (LGT): Middle-level terrace along the Minnesota River between Carver and Chaska. Borings and well logs show that sediments of the Langdon terrace consist here of a sequence of thick sand over sand and fine gravel.

Piersons Lake Ice-Contact Deposits (PLI): A chain of discontinuous sand and gravel deposits across Laketown and Chanhassen townships. These deposits probably represent collapsed sediment from a supraglacial meltwater stream which emptied into Glacial River Warren, the much larger stream that once occupied the present Minnesota River valley. Several gravel pits have been opened in these deposits. Although gravel is present, in most places it is less than 20 feet thick. Some deposits are composed largely of sand or contain abundant clay. A pit northeast of Chaska contains gravel in which about 5 percent of the particles are greater than 1.25 inches, and 1 percent is greater than 3 inches in size. None of the clasts exceed 4 inches, and some clay seams were noted. Samples from a pit on the north side of Piersons Lake averaged 2 percent spall, although shale percent is probably higher than that at other locations.

Richfield Terrace (RFT): Highest-level terrace along the Minnesota River. The Richfield terrace consists of sand and gravel deposits that are considered to be the best in Carver County. The best resources are mainly in Dahlgren and San Francisco townships, where the deposits are well over 100 feet thick. The deposits were laid down during the ablation of the Des Moines lobe, probably at about the same time as the San Francisco ice-contact deposits (described below). The sands and gravels were then redeposited by Glacial River Warren (the large precursor of the Minnesota River that was fed by glacial meltwater) across a terrain that included blocks of stagnant ice. Higher quality, Superior-provenance sand and gravel are being mined from the bottom of the large gravel pit southwest of Carver.

Over most of the terrace plain, the sand and gravel deposits are covered by clay and fine sand that together range from 5 to 10 feet or more in thickness. For this reason, most pits are opened along the terrace escarpment where gravel is exposed. A gravel pit in the southeast corner of section 1, San Francisco Township, exposes 90 feet of very coarse sand and fine gravel. Large areas within the terrace are mapped as a class 4 resource, and consist of more than 10 feet of sand that overlies interbedded sand and gravel, although in some cases the sequence is consistently gravel-poor, or the sand overlies till or clay.

Spall material content is fairly high, but variable. Samples from borings in sections 20 and 29, San Francisco Township, average 4% shale (by weight) and 1% iron oxide, but samples from borings in section 25, Dahlgren Township and an adjoining area in Carver Township average 1.2% shale and 0.6% iron oxide. Although a thick, sandy cover is widespread, large amounts of sand and gravel remain to be mined, especially along the terrace escarpments.

San Francisco Ice-Contact Deposits (SFI): This group of deposits probably represents collapsed sediment laid down by a supraglacial meltwater stream as a delta or outwash complex in the Minnesota River valley. The “upstream” deposits parallel the Silver Creek drainage. The “delta” was laid down on top of stagnant ice. As the ice melted, the deposits were undermined. Consequently these deposits are highly variable both vertically and horizontally. A pit in the northeast corner of section 16, San Francisco Township, shows disturbed bedding and also contains many pockets of shale, with pebbles of shale as large as 1 inch in diameter. Pits in section 9 expose more than 15 feet of cobbly and bouldery sand and gravel as well as till.

DAKOTA COUNTY

Two major outwash surfaces extend across much of Dakota County. The Rosemount outwash plain was laid down during wastage of the Superior lobe, and is cut by several outwash valley trains of the Des Moines lobe. South of Hastings, these deposits coalesce into a second broad outwash plain, the Vermillion River outwash, which was deposited by meltwater from the Des Moines lobe. Valley-train outwash along the Cannon River and older sand and gravel deposits within the Hampton moraine also contribute large gravel deposits to Dakota County.

Apple Valley Outwash (AVO): A valley-train deposit that originates at the terminal moraine of the Des Moines lobe. The meltwater that deposited this unit joined similar streams at Farmington. Little subsurface information is available to classify the material in the lower two-thirds of the valley, but it appears to be gravel poor. The water table is high in the area. A very large gravel pit, however, was once active within the City of Apple Valley. In this pit, overburden averaged 3 to 4 feet, and the gravel was over 40 feet thick. Less than 1 percent of spall was documented in numerous samples from borings near the pit. A hand sample from the pit wall yielded about 1 percent shale in the sand fraction and 4 percent shale pebbles. About 18 percent of the pebbles are carbonate rock (Savina and others, 1979, p. 11). Development in the area will soon preclude further mining.

Bluff Gravel (BFG): Sand and gravel deposits typically associated with till, and exposed along the steep valley walls of the Minnesota and Mississippi rivers. Sand and gravel in these deposits commonly adds up to a thickness greater than 50 feet.

Burnsville Kames (BVK): A hook-shaped group of ice-contact deposits that trends northwest from Buck Hill to Savage, and then east along the Minnesota River valley. These kames are interpreted to have been laid down when the Des Moines-lobe terminal moraine was being formed. Some of the kame deposits directly overlie gravel laid down within the St. Croix moraine by the Superior lobe, and contain abundant material reworked from the older Superior-lobe deposits. Very thick sections of gravel (50 to over 100 feet) pass abruptly into till over short horizontal distances. For this reason, boundaries of the gravel deposits are difficult to establish without closely spaced subsurface control. These deposits are generally no longer accessible.

Burnsville Outwash (BVO): A small body of outwash southeast of Savage, which received its gravel from meltwater streams originating in Scott County. Borings from a pit in section 22 yielded samples that average about 2.5 percent shale, with total spall of 4 percent.

Cannon River Outwash (CRO): A narrow band of outwash along the Cannon River which broadens into a plain between Randolph and Cannon Falls. This sand and gravel deposit was laid down mostly by meltwater emanating from the Des Moines lobe. Locally the deposit is more than 50 feet thick, although the water table is commonly encountered at depths less than 20 feet. Northwest of Cannon Falls, the outwash is locally gravel-poor, or thin where it overlies bedrock. There is limited subsurface information for much of the area covered by this deposit.

A large pit in sections 20 and 21 in Waterford Township is described as “very uniform throughout,” and contains about 0.25 percent shale and 1.5 percent iron oxide. Gravel used to make cement blocks is taken from below the water table, which is about 18 feet below surface. Samples from two pits nearby average 2 percent total spall above the water table, while samples from one pit below the water table average 3 percent total spall. Samples from borings at two sites in section 11 near Cannon Falls average 1.5 percent total spall. Samples from borings at a site in section 12 near U.S. Highway 52 averaged 2.3 percent total spall. A combined sample from several shallow borings taken across the outwash plain contain 1.1 percent shale, and a total spall content of 1.7 percent.

Castle Rock Valley Fill (CSV): Predominantly sandy material that has been eroded from other deposits and washed down slope to fill in low-lying areas within the older sand and gravel deposits and bedrock uplands in the southern portion of Dakota County. These deposits are generally gravel poor, and are commonly overlain by more than 10 feet of overburden. Subsurface information is very limited.

Cottage Grove Outwash (CGO): An outlier of a large outwash plain in Washington County that is geologically equivalent to the Rosemount outwash plain in Dakota County. This outwash plain was separated from the main body of the Rosemount outwash plain by the excavation of the present Mississippi River valley. Most of the deposit is covered by housing.

Des Moines Ice-Contact Deposits (DMI): Sand and gravel deposits associated with the terminal moraine of the Des Moines lobe along the western border of Dakota County. Many of these deposits, especially in the Orchard Lake area, are too variable or too small to map. Some may be locally significant, but many deposits are no longer available due to suburban development. Borings from a small esker-like deposit in section 8, Greenvale Township, penetrated a maximum of 11 feet of gravel, and samples contained about 2.5 percent shale.

Eagan Kames (EAK): Several large ice-contact deposits within the St. Croix moraine in northern Dakota County that are interpreted to have been laid down in predominantly stagnant water. The deposits were probably laid down in ice-walled lakes, because they are predominantly composed of well-sorted, fine to medium sand (Gelineau, 1959). When the ice melted, the topography was inverted, and former lake-bottom deposits became hill tops. Some gravel may be available along steep side slopes, which may have once been lake beaches.

Grey Cloud Terrace (GCT): Lower-level terrace along the Mississippi and Minnesota rivers. The largest sand and gravel deposit beneath this terrace surface (southeast of Hastings along the Mississippi River valley) is essentially the only one still available for mining. Little or no subsurface information is available for any of the deposits of the Grey Cloud terrace within Dakota County. Equivalent deposits are discussed more thoroughly under Washington County.

Hampton Moraine (HAM): A prominent east-west trending ridge that is predominantly in Hampton and Douglas townships, with outliers extending to the north over eastern Dakota County. This moraine and its outliers are composed mostly of stratified sand and gravel. They were deposited by an earlier advance of Superior-lobe ice, and thus contain high percentages of igneous and metamorphic rocks and red sandstone. Local limestone and dolomite have been incorporated in the deposit, but have leached out of the top 4 to 6 feet. Below the leached zone, carbonate pebbles range from 10 percent to 27 percent. Shale is essentially absent (Savina and others, 1979). Samples from a pit in section 3, Hampton Township, contain only a trace of shale and 0.3 percent iron oxide. Samples from borings in mostly sandy material at a site in section 26 of Hampton Township contain 0.6 percent spall. A pit in section 35, Vermillion Township, yielded samples with no shale and 0.6 percent iron oxide. Los Angeles Rattler tests (LAR, see Appendix C) on these deposits provide higher numbers than do the younger, Superior-provenance deposits, presumably as a result of the greater amount of weathered rock clasts in the older deposits. Several large pits have been opened in the Hampton moraine deposits.

Lakeville Outwash (LVO): Valley train outwash in the Lakeville area that originated from the terminal moraine of the Des Moines lobe, and coalesces with the Vermillion River outwash at Farmington. Several large pits have been opened in this deposit west of Marion Lake. Samples from borings at one pit near the lake penetrated sand and fine gravel, that contained about 5 percent crushing material, ranging between 1.25 and 6 inches, and a shale content of about 2 percent. A sample of pebbles from the pit wall contained no shale and 24 percent carbonate rock. A sample from a pit in the northeast corner of section 26 contained 6 percent shale and 8 percent carbonate pebbles, and almost 4 percent of the sand fraction was shale (Savina and others, 1979). However, samples from borings at four other sites averaged only about 1.5 percent total spall. One such site was noted to be heavy in gravels ranging between 1.25 and 8 inches.

Little subsurface information is available for the remainder of the deposit south and east of Marion Lake. Indications are that much of this area is underlain by more than 20 feet of gravel, but the water table is less than 20 feet from the surface. Pebbles in a sample from a pit in section 29 at Lakeville contained 8 percent shale and 31 percent carbonate rock. The sand fraction contained more than 5 percent shale by weight (Savina and others, 1979). Continuing urban development in the area excludes large portions of this deposit from use by the aggregate industry.

Langdon Terrace (LDT, LGT): Middle-level terrace along the Mississippi and Minnesota rivers. Most of the good gravel deposits at this terrace level in Dakota County are along the Minnesota River, but most of these have been depleted or have been covered by housing developments. A large gravel pit at the intersection of Highways 36 and 13 was described as having gravel of excellent quality, with cobbles no larger than 4 inches. Samples from borings contained an average of 0.2 percent shale and 0.6 percent iron oxide. Hand samples of pebbles from the area contained about 1 percent shale and 38 percent carbonate rock. A hand sample of pebbles from a site in section 17 about a mile to the northeast of Highways 36 and 13 included 1 percent shale and only 2 percent carbonate rock. Farther down the valley, a sample from a site near Highway 13 in section 33 yielded 2 percent shale and 31 percent carbonate pebbles (Gelineau, 1959, p. 19).

Much of the cities of South St. Paul and Inver Grove Heights have been built on a remnant of the Langdon terrace. The sandy deposit that forms the terrace is , for the most part, poor in gravel, although several large gravel pits have been opened into the steep terrace slope. These pits have expanded into the terrace to mine the gravel underneath the thick surficial sand. Pebble samples from the deposits of the Langdon terrace here range from 0 to 1 percent shale, and 0 to 33 percent carbonate rock (Gelineau, 1959, p.21). Most of the remainder of these deposits is no longer available for extraction.

Large deposits at this terrace level are present south of Spring Lake, at Hastings, and southeast of Hastings along the Mississippi River valley. Most of these deposits are thought to be gravel poor, with the exception of the eastern portion of the terrace southeast of Hastings. Gravel may also be present along steep slopes of gullies that dissect the terrace.

Mendota Heights Outwash (MHO): An outwash plain in northern Dakota County associated with the ablation of the Grantsburg sublobe, and equivalent to the St. Paul outwash in Ramsey County, and the Minneapolis outwash in Hennepin County. Pebble samples from the southern portion of the deposit contain 0 to 14 percent shale, and average 20 percent carbonate rock (Gelineau, 1959, p. 19).

Mississippi Floodplain (MSF): Recent alluvium deposited within the Mississippi River floodplain.

Richfield Terrace (RFT): Upper-level terrace along the Minnesota and Mississippi rivers. Only three small remnants of the deposits that make up the Richfield terrace are mapped in Dakota County; they are in Burnsville, South St. Paul, and south of Spring Lake. The first two deposits have been built over. The third is thought to be gravel poor, although few subsurface data are available.

Rich Valley Train (RIV): Deposit laid down in a major drainageway that carried Grantsburg sublobe meltwater through the St. Croix moraine. This valley may also have served earlier as a drainageway for Superior-lobe meltwater. Stagnant ice within the St. Croix moraine probably continued to feed the drainage system during the advance and retreat of the Grantsburg sublobe. When the stagnant ice blocks beneath the outwash melted, they created numerous large, closed depressions within the valley. The valley ranges from about 0.5 to 1 mile wide from its head in the Mendota Heights outwash to a point about 3 miles west of the Vermillion River. Here, the valley widens as it merges with the Vermillion River outwash plain. The gravel content generally seems to decrease southwards.

Numerous test-boring samples from sites in section 29 and 32 in Inver Grove Heights contain only a trace of shale, and average 0.4 percent iron oxide. Seventeen samples of pebbles were collected by Gelineau (1959) along the valley in the Inver Grove Heights quadrangle. Each sample contained about 100 pebbles retained on a 0.5-inch screen. Four of the samples contained one shale pebble each, and one sample contained two shale pebbles, and shale was absent from the 12 remaining samples. None of the shale pebbles were from Cretaceous shales (atypical for the Grantsburg sublobe). In three of the samples, limestone and dolomite pebbles ranged from 0 to 41 percent, and averaged 12 percent. Other dominant pebble types were granite, basalt, graywacke, felsite, and sandstone. Subsurface information is limited in most areas.

Rosemount Outwash (RSO): A very large outwash plain in central Dakota County that was deposited by Superior-lobe meltwater during the formation of the St. Croix moraine. Subsequent to deposition of the outwash, the plain was dissected by several major meltwater streams that formed large valleys. It is the largest single sand and gravel deposit in the seven-county area.

Gelineau (1959, p. 21-23) collected 15 samples of pebbles larger than 0.5 inch from the northern part of the outwash plain near the St. Croix moraine in the St. Paul SW and Inver Grove Heights quadrangles. Non-Cretaceous shale was present in four samples, and yielded an average of 0.5 percent shale for the 15 samples. Limestone and dolomite pebble content ranged from 0 to 24 percent, with an average of 8 percent. Test-boring samples from two sites in section 14 in Rosemount yielded only a trace of shale and unsound chert, and 0.1 to 0.2 percent iron oxide. Test-boring samples from section 21 yielded no shale and 0.7 percent iron oxide.

Test-boring samples from sites scattered over the rest of the outwash plain registered similar results. In section 20, Lakeville, there was only a trace of shale, 0.4 percent iron oxide, and no unsound chert. In section 20, Empire Township, there was only a trace of shale and iron oxide and no unsound chert. In section 19, there was a trace of shale and 0.3 percent iron oxide (material here was described as very uniform with much metal; cobbles from 3 to 12 inches were estimated to compose from 10 to 13 percent of the deposit). Borings in section 13 yielded samples with only a trace of iron oxide and no shale or unsound chert. In section 20, Vermillion Township, samples contained 0.1 percent shale and 0.2 percent iron oxide. In section 30 in Rosemount, samples contained 0.1 percent shale and a trace of iron oxide.

In a study by Savina and others (1979), 38 samples of about 100 pebbles each were collected from sites throughout the outwash plain. Non-Cretaceous shale was present in five of the samples, yielding an average of 0.2 percent shale per sample. Limestone and dolomite pebbles compose 5 to 29 percent of the sample, to produce an average of 19 percent. Rock types characteristic of the Lake Superior region (red sandstone, basalt, gabbro, felsite, and redrock) average 31 percent per sample. Shale was identified in six out of eleven sand samples, with the highest shale content being only 0.2 percent.

In general, outwash thickness across the plain decreases from northwest to southeast. Thickness is quite variable, however, due to the irregularity of the underlying bedrock surface. The deposit is generally over 50 feet thick. Average grain size within the deposit also decreases to the southeast. Outwash near the St. Croix moraine contains abundant coarse gravel and cobbles, whereas deposits farther away are composed mainly of sand and fine gravel throughout most of the central part of the plain. A loamy “cap” about 5 feet thick covers the sand and gravel. Underneath the cap the deposit typically coarsens downward. Large areas mapped as class 3 resources may include gravel-poor material that is more than 20 feet thick at the surface. Due to limited subsurface data, these areas could not be separately delineated.

St. Mary’s Terrace (SMT): Lowest-level terrace along the Mississippi River. Two deposits are mapped at the St. Mary’s terrace level in Dakota County. They are in section 26 in Hastings, and in sections 5 and 6 in Ravenna Township. No subsurface information is available, but a large active gravel pit operates in the Ravenna deposit. Quality appears to be excellent, but the water table is high.

Superior Ice-Contact Deposits (SUI): Ice-contact deposits associated with the St. Croix moraine in northern Dakota County. Some of these deposits contain significant amounts of gravel, and accordingly several large pits have been opened in them. Sand and gravel in these deposits varies both in thickness and quality over small distances. Rock types are similar to those in the Rosemount outwash, with a high percentage of Lake Superior lithologies, variable amounts of carbonate rock, and little to no shale. Five pebble samples collected by Gelineau (1959, p. 23) ranged from 6 to 28 percent carbonate, with an average of 20 percent. One sample contained four percent non-calcareous shale, and it was absent from the other samples. Test borings at a site in section 17, Burnsville, provided samples that contained 0.1 percent shale in the sand fraction and 0.2 percent iron oxide. Samples from section 30 in Eagan contained only a trace of shale and iron oxide, as did samples from two sites in section 31 in Inver Grove Heights. Samples from borings in section 1 in Eagan contained 0.2 percent shale and 0.4 percent iron oxide.

Valley Delta Gravel (VDG): Gravel deposit in the bottom land of a gully that cuts deeply into the Vermillion River outwash plain, and in the delta at the gully mouth. This gravel may have been laid down during the formation of the Rosemount outwash plain, and then buried by the Vermillion River outwash, and then exposed again during formation of the gully. The small delta at the gully mouth was formed when material eroded during flash flooding was dumped into the Mississippi River valley. Much of this deposit appears to include good quality gravel. Test borings from a pit in section 2 of Marshan Township showed only a trace of shale in the sand fraction and 0.5 percent iron oxide.

Vermillion River Outwash (VRO): This deposit includes a valley train within the Vermillion River valley, which opens into a broad outwash plain at Vermillion. Together with the Apple Valley outwash, the Lakeville outwash, and the Rich valley train of Rich Valley, the Vermillion River outwash partially fills valleys cut into the broad Rosemount outwash plain by meltwater issuing from the terminal moraine of the Des Moines lobe. South of Hastings the Vermillion River outwash plain is at about the same elevation as the Richfield terrace. The meltwaters which laid down the outwash plain may have graded into the Mississippi River.

East of Farmington, the outwash is mostly sand. Fine gravel may be encountered at depths of greater than 10 feet, or in steep gully slopes that cut into the deposit. Shale content seems to be highest between Farmington and the Rich Valley train (Savina and others, 1979, p. 31). Influx of shale-poor material from the Rich Valley train diluted the shale content. A sample from section 19 near the town of Empire yielded 12.5 percent shale by weight in the sand fraction. A sample from section 15 near Vermillion yielded 4.5 percent shale by weight in the sand fraction. A sample from section 6 in Marshan Township at the mouth of Rich Valley did not include any shale in the sand, although 2 percent non-Cretaceous shale was noted in the pebble fraction (which contained only 1 percent carbonate rock). About a mile to the north, a sample contained only a trace of shale, and two miles to the east in section 33, several samples contained a maximum of only 0.03 percent shale by weight in the sand fraction. No shale was present in the pebble-sized samples, although they do contain 16 percent carbonate rock (Savina and others, 1979, p. 11-13).

Prospects for quality gravel deposits in the outwash are best west of Farmington, although the water table is typically less than 20 feet below the surface. Samples from a pit in section 10 of Eureka Township in the high-water-table area contain close to 2 percent shale by weight in the sand fraction, but no shale pebbles. About 16 percent of the pebbles are limestone or dolomite (Savina and others, 1979, p. 11). Test-boring samples from a pit in section 7 of Eureka Township contained an average of 0.6 percent shale in the material retained on the 3/8-inch screen, and 0.1 percent unsound chert. Numerous samples from another large pit in section 7 averaged 0.5 percent shale and 0.5 percent iron oxide.

Waterford Outwash (WFO): Sand and gravel deposited by meltwater from the terminal moraine of the Des Moines lobe. Meltwater that laid down this outwash flowed out the Cannon River drainage, entering the river valley west of Randolph. The water table is less than 20 feet below the surface in most of the deposit. The only part of the deposit rated good to moderate is east of Chub Creek in Sciota Township, although coarse materials are probably also present farther to the west.

Test borings at a site in sections 3 and 4, Greenvale Township, penetrated from 5 to 18 feet of gravel. Samples contain an average of 1.4 percent shale and 0.7 percent iron oxide. Test borings at a site in section 15, Sciota Township, penetrated over 20 feet of coarse gravel and intersected the water table at depths between 18 and 21 feet. Samples contained an average of 1.6 percent shale, 0.4 percent iron oxide, and no unsound chert.

HENNEPIN COUNTY

Most of the moderately good to excellent sand and gravel deposits in Hennepin County have been depleted or are no longer available for extraction. A large kame complex in Maple Grove has supplied large quantities of gravel to the seven-county metropolitan area for many years, but will soon be depleted. Large outwash deposits in Minneapolis and its western suburbs have also been prolific suppliers of sand and gravel, but have been covered by urban expansion. Outwash sand and gravel along the Crow River in northwest Hennepin County may still produce significant amounts of gravel in the future.

Bloomington Outwash (BLO): Collapsed sediment of a supraglacial meltwater stream that flowed roughly parallel to the buried St. Croix moraine, and drained toward the Minnesota River valley. The sediment was laid down during the ablation of the Grantsburg sublobe. When the underlying ice melted, the sand and gravel collapsed and formed a “knob and kettle” topography of steep hills and depressions. Because of this disturbance the deposit typically varies greatly in thickness. Till is exposed in most large pits opened in this deposit. Samples from test borings at two sites in section 10, Eden Prairie, contained less than 1 percent spall, of which about half is shale. Samples from a site in section 12 yielded similar results. The remaining undeveloped areas are surrounded by housing or commercial development.

Bluff Gravel (BLG): Sand and gravel deposits exposed along the steep valley walls of the Minnesota River. No subsurface information is available for these deposits. They are commonly associated with till.

Crow River Outwash (COO): Outwash sand and gravel along the Crow River at the northwest boundary of the county, laid down by meltwater draining the Grantsburg sublobe. Large areas within the deposit have water tables shallower than 20 feet. The gravel typically contains sand layers, but in general is fairly coarse.

Shale is common in the deposit, and ranges from 1.6 percent to 4.3 percent based on available sample data. Samples from test borings at sites in Greenfield record the lowest percentage of shale. In section 16, samples contained 2.4 percent shale and 0.8 percent iron oxide. In section 10 samples averaged 1.6 percent shale and 0.4 percent iron oxide. Pits in section 10 and in section 2 expose deposits that contain a high percentage of Superior-provenance gravel. In Hassan Township, a pit in section 17 contains about 3 percent shale, and a total spall content of 4.6 percent. Four pits in the same township, clustered around Highway I-94 northwest of Rogers, average 3 percent shale (with a high of 4.3 percent), and about 0.8 percent iron oxide. A pit north of Rogers in section 11 yielded samples averaging 3.1 percent shale and 0.8 percent iron oxide.

Crystal Lake Sand (CLS): Gravel-poor sand laid down at the mouth of a glacial meltwater stream in Glacial Lake Anoka. Parts of the cities of Crystal and Robbinsdale are built across this deposit.

Eden Prairie Outwash (EPO): Thick gravel-poor outwash plain above the Minnesota River valley. The outwash plain was fed by meltwater streams that drained the Grantsburg sublobe, which lay to the northwest. Sand and gravel were deposited on top of large stagnant ice blocks. When these blocks melted, they created great depressions in the plain. Some gravel can be found toward the head of the deposit to the northwest, and fine gravel may be available where steep slopes cut through the deposit.

Shale content is fairly high. Samples from test borings at a site in section 6 in Eden Prairie yielded 6 percent shale and 1 percent iron oxide. Samples from a site to the southeast in section 5 yielded 4.6 percent shale and 0.8 percent iron oxide. Samples from a site near Round Lake in section 8 averaged 4.6 percent shale and 1 percent iron oxide. A pit in section 17 east of Mitchell Lake contained 5.7 percent shale and 0.8 percent iron oxide. Most of the deposit is covered by housing and commercial development.

<u>Golden Valley Outwash (GVO)</u>: Sand and gravel laid down by a two-forked meltwater stream that originated in Plymouth. The stream deposited gravel across stagnant ice blocks of the Grantsburg sublobe and emptied into Glacial Lake Anoka north of Golden Valley. The deposit is finer grained downstream. In samples from a pit in section 27, Plymouth, 7 percent of the material was retained on the 1.25-inch screen, and 2 percent is larger than 3 inches. A pit in section 30 was described to show intermediate grading with pockets of sand. A pit in section 26 was noted to contain good quality gravel. In section 31 in Golden Valley, a pit was opened in mostly coarse sand and fine gravel. In section 32, the deposit is mostly sand with some fine gravel in the upper 2 to 4 feet. Borings in the southwestern corner of section 28 penetrated mostly fine sand that only rarely includes pockets of gravel. A pit in the same section to the northeast contained essentially no gravel. Several large gravel pits have been opened in the western part of the deposit, but the remaining gravel is no longer available due to urban expansion.

<u>Grantsburg Ice-Contact Deposits (GBI)</u>: Unnamed kames and eskers deposited for the most part by the Grantsburg sublobe. These deposits may include small areas of Superior-lobe gravel exposed by erosion within the St. Croix moraine. The ice-contact deposits are scattered throughout Hennepin County, but are particularly concentrated along the buried St. Croix moraine. The kames and eskers were formed as glacial debris was sorted and transported by subglacial streams. In some cases the debris was sorted by supraglacial streams before being dumped into holes or crevasses in the ice. Due to their varied origins, these deposits range in thickness and quality both laterally and vertically. Pits opened in such material commonly expose till and other fine-grained deposits. Because of this variability, it is difficult to judge the size and quality of ice-contact gravel deposits without abundant subsurface data.

Available data illustrate the variability of this deposit. A pit in section 35, Minnetrista, exposes a heterogeneous deposit of sand, gravel, and clay, “which might be suitable for fill purposes only.” Boulders in the bottom of the pit range from 1 to 3 feet across. About 5 percent of the material was retained on the 1.25-inch screen, and 2 percent was greater than 3 inches in diameter. Samples from two sites in the St. Croix moraine indicate a scarcity of shale. Samples from section 22 in Minnetonka contained only a trace of shale in the sand, and 0.4 percent iron oxide. Samples from sections 34 and 35 yielded only 0.2 percent shale, a trace of iron oxide, and 0.2 percent unsound chert. This lack of shale is due to the incorporation of large amounts of shale-poor Superior-lobe till when the Grantsburg sublobe moved over the St. Croix moraine.

Samples from a site near Rockford in western Hennepin County indicate that similar deposits in this part of the county contain a high percentage of shale. The deposit in section 23, Greenfield, yielded more than 6 percent shale, 0.7 percent iron oxide, and a trace of unsound chert. Many of the Grantsburg ice-contact deposits in the county are inaccessible to mining due to urban development, and most of the remaining deposits were deemed insignificant.

Grey Cloud Terrace (GCT): Lower-level terrace along the Minnesota River. Only one small deposit was mapped at this terrace level in Hennepin County. Much of it has been depleted because it is composed of good quality gravel that is over 30 feet thick. Samples from test borings above the water table at the site contain only a trace of shale and iron oxide, and no unsound chert. One sample from below the water table contains 0.9 percent shale in the sand fraction, and a trace of shale in the gravel fraction.

Hillside Gravel (HLG): Proglacial outwash laid down in front of the advancing Grantsburg sublobe. This may include some recessional outwash of the Superior lobe at the base of the deposit. The deposit ranges in thickness from about 25 to 150 feet, the variation due in part to a highly irregular upper surface (Stone, 1966). The deposit is exposed along the steep valley walls of the Mississippi River in northeast Minneapolis. A very large gravel pit (abandoned for over 35 years) was opened in the deposit here. Where near the surface, the deposit is completely covered by urban development.

Langdon Terrace (LGT): Middle-level terrace along the Mississippi and Minnesota rivers. In Hennepin County deposits of the Langdon terrace are generally composed of gravel-poor sand. Gravel is fairly close to the surface in a few large areas in Bloomington, and along some steep slopes. Sand and gravel typically sum to a thickness greater than 50 feet. Samples from borings at a site along Highway I-35W in section 21 average 1.4 percent shale and 0.3 percent iron oxide. In Minneapolis, the deposit can be less than 20 feet thick. The terraces in Bloomington, Richfield, and Minneapolis are quite broad, because the glacial rivers that formed them were able to cut rapidly across the large outwash plain which once covered the area. In Hennepin County most of the deposits of the Langdon terrace are covered by urbanized areas.

Minneapolis Outwash (MPO): A large outwash plain that underlies much of Minneapolis, St. Louis Park, and Edina. The plain was fed by two major meltwater streams, one originating at Lake Minnetonka, and the other near Glen Lake in Minnetonka. The streams drained eastward from the stagnating Grantsburg sublobe, and coalesced in the St. Louis Park area. Minor subglacial streams in the Edina area also supplied sand and gravel to the outwash plain. Many large gravel pits have been opened in this deposit, but all have been either built over or surrounded by urbanized areas.

Samples from a site in Deephaven, in section 18, contain 3.8 percent shale and 0.8 percent iron oxide. Spall count in the deposit diminishes to the east, however. Samples from a site in section 5 in Bloomington yield 0.9 percent shale and 0.6 percent iron oxide. Samples from sites spread across the outwash indicate generally good quality and grading in the deposit, with a gradual decrease in grain size eastward toward where it broadens into a wide plain. A site in section 21 in south Minneapolis contained mostly sand with very little material over 1.25 inch and nothing greater than 3 inches. The Minneapolis outwash is essentially no longer available for mining due to urban expansion.

Minnetonka Kame (MTK): A large ice-contact deposit laid down within the St. Croix moraine by Superior-lobe ice. The kame formed at a major drainage point within the moraine, and an alluvial fan was created off the edge of the ice when subglacial streams dumped their loads of sand and gravel. The kame was subsequently overridden by the Grantsburg sublobe, and partially buried. The Minnetonka kame was probably formed in a similar manner to the large kame in Maple Grove, which has provided large amounts of sand and gravel to the seven-county metropolitan area.

The deposit is quite thick; locally, water wells have penetrated over 100 feet of sand and gravel. Test borings at a site near Wing Lake in section 33, Minnetonka, penetrated coarse gravel with pockets of sand and a small percentage of boulders greater than 8 inches. Several pits were opened in the deposit, but it has been largely unexploited. The Minnetonka kame deposit is almost completely covered by housing developments.

Mississippi Floodplain (MPF): Recent alluvium deposited within the Mississippi River floodplain. In northeastern Hennepin County, two small areas are mapped along the Mississippi River. No subsurface data are available, but these deposits are regarded as being gravel poor. A dragline would probably be required to mine these deposits.

Osseo Kame (OSK): A large fan laid down at the mouth of a subglacial stream draining the Superior lobe during the formation of the St. Croix moraine. Later, the Grantsburg sublobe overrode and buried this deposit with clay till and/or fine sand and gravel. Most of the deposit has been depleted by extensive mining operations, but parts of it that were once classed as inferior are now valuable due to their proximity to the urban area.

Numerous samples indicate very low spall content and large amounts of crushing material. Samples from borings at a site in section 14, Maple Grove, average 0.1 percent shale and 0.3 percent iron oxide. A nearby pit exposed 25 feet of "very good gravel with about 40 percent crushing and some oversize." Samples contain 0.1 percent shale, no iron oxide, and 0.2 percent unsound chert. Samples from a site in the northwestern corner of section 23 contain only 0.1 percent shale and no iron oxide. A pit in the southeastern corner of section 23 exposed 50 feet of very good gravel with about 30 percent crushing material. Samples from a site at the western edge of section 24 yielded 0.2 percent shale in the sand fraction and only a slight trace of shale in the gravel, with 0.3 percent iron oxide. Samples from the southwestern corner of section 23 yielded only a trace of shale and iron oxide.

Osseo Outwash (0S0): Extensive sand and gravel deposit of uncertain origin. It may represent an extension of the Osseo kame complex which merges into a plain as a result of deposition by meltwater adjacent to the Grantsburg sublobe. Whatever its origin, this deposit is commonly more than 50 feet thick; one water well penetrated 100 feet of gravel. The deposit also probably has a low spall content, at least at depth. It is no longer available for mining due to urbanization.

Richfield Terrace (RFT): Upper-level terrace along the Minnesota and Mississippi rivers. The large areas mapped at the Richfield terrace level in Hennepin County generally include sand or gravel-poor sand. Abundant subsurface information is available in the downtown area of Minneapolis for both the Langdon and Richfield terrace deposits. The sand and gravel is typically overlain by 15 to 20 feet of fine sand. Locally, gravel deposits are closer to the surface, but these terraces were so disturbed by fluvial cutting and filling that they are mapped as a class 5 resource. In most of the areas north and south of downtown Minneapolis the terrace deposit is gravel-poor throughout the top 20 to 30 feet, at least. Although much of the deposit has been built over, pockets of fair sand and gravel may still be present in a few areas, such as section 10 in Dayton Township, in Brooklyn Park, and in Eden Prairie above the Minnesota River.

St. Paul Outwash (SPO): Discussed under Ramsey County.

RAMSEY COUNTY

Sand and gravel deposits were originally extensive in Ramsey County, but almost all of them have now been built on or depleted.

Arsenal Kame (ARK): Prominent hill originally deposited as an alluvial fan when subglacial streams draining the Superior lobe dumped their load of sand and gravel at the edge of the ice. The deposit is dominantly a pebbly fine- to coarse-grained sand. Although reworked at the top by the Grantsburg sublobe, the deposit contains little shale. Numerous samples from test borings in the deposit average 0.1 percent shale in the sand fraction, 0 percent shale in the gravel, and 0.1 percent iron oxide. Borings have penetrated more than 140 feet of sand and gravel within the deposit. This deposit probably is no longer available for mining, as a result of surrounding suburban development.

Bluff Gravel (BFG): Sand and gravel exposed along the steep valley walls of the Mississippi River. Only one such deposit was mapped in Ramsey County, in the southeastern corner of the county. Sand and gravel are interbedded with till. No subsurface information is available.

Cottage Grove Outwash (CGO): Part of a large outwash deposit that is present mostly in Washington County. The outwash was laid down while the Superior lobe was building the St. Croix moraine. Stagnant ice blocks beneath the deposit have melted to create deep depressions. Only a few water-well logs are available for the Ramsey County portion of the deposit, but indications are that the deposit may be as thick as 100 feet. Interbeded till may be present, and overburden may locally be greater than 10 feet. Housing development in the area may soon rule this deposit out as an aggregate resource.

Grantsburg Ice-Contact Deposits (GBI): Unnamed kames and eskers deposited during the wastage of the Grantsburg sublobe. They are scattered throughout the northwest half of Ramsey County. Only a few small areas remain available for mining. The gravel-bearing beds in these deposits are typically variable in thickness and composition, and are commonly interbedded with till and other finer-grained material. The thickness of overburden also varies widely. Shale content is probably low in most of the deposits. Some of the areas mapped as GBI consist mostly of thinly buried Superior-lobe sand and gravel deposits.

Grey Cloud Terrace (GCT): Lower-level terrace along the Mississippi River. The few small areas mapped as deposits of the Grey Cloud terrace in Ramsey County are not available for mining. Percentages of sand and gravel in these deposits vary, as do their thicknesses. For the most part, the deposits are gravel poor, and not a significant resource.

Hillside Gravel (HLG): Discussed under Hennepin County.

Langdon Terrace (LGT): Middle-level terrace along the Mississippi River. Two small deposits are mapped in St. Paul, both of which are completely built over. Good gravel is probably locally present in the deposits.

<u>Mississippi Floodplain (MSF)</u>: Recent alluvium deposited in the Mississippi River floodplain. Two small deposits are mapped near the airport in St. Paul. Both have been built over. The deposits are probably gravel-poor, although a few pockets of fine gravel may be present.

<u>North Oaks Ice-Contact Deposits (NOI)</u>: An esker-kame complex partially surrounding Pleasant Lake. The deposits were laid down by subglacial meltwater streams during the wastage of the Grantsburg sublobe (and probably also the Superior lobe) . Although both gravel thickness and percentage varies within the deposits, large areas containing gravel beds more than 40 feet thick are common. Most of these areas, however, are covered by housing. Samples from test borings at a site in section 9, White Bear Township, contain 1.2 percent shale in the gravel fraction, and 0.3 percent iron oxide. The material sampled in these borings may be atypical, however, as it was gravel poor. The more gravely deposits tend to yield lower percentages of shale.

<u>Richfield Terrace (RFT)</u>: Discussed under Hennepin County.

<u>St. Paul Outwash (SPO)</u>: A large outwash plain that underlies much of the City of St. Paul and extends into its northern suburbs. The plain was laid down during the ablation of the Grantsburg sublobe and is equivalent to, and probably once merged with, the Minneapolis and Mendota Heights outwash plains. The St. Paul outwash plain was fed by meltwater streams that originated in White Bear Lake and Roseville. Streams flowing southwest from White Bear Lake paralleled the terminal moraine of the Grantsburg sublobe, and deposited sand and gravel between Grantsburg-sublobe till and Superior-lobe till. A large pit in this deposit in section 34, White Bear Township works a layer of cobbly sand and gravel about 25 feet thick that contains relatively abundant shale pebbles. This area is one of the last remaining places within the St. Paul outwash that may still be available for aggregate mining. Outwash to the southwest in Maplewood is predominantly gravel-poor.

Much of the St. Paul campus of the University of Minnesota and the state fairgrounds are underlain by coarse sand and gravel that is as thick as 100 feet. Several large pits opened southeast of the fairgrounds yielded significant amounts of aggregate up to the early 1950's. Thick sand and gravel deposits extend to the southeast toward downtown St. Paul.

<u>Superior Ice-Contact Deposits (SUI)</u>: Kames deposited by the Superior lobe within the St. Croix moraine. These deposits are scattered throughout the southeast portion of Ramsey County. Little subsurface information is available for these deposits, the majority of which underlie areas of urban development. Typically, ice-contact deposits exhibit wide variability in gravel quantity, and are commonly associated with till. Superior-lobe sand and gravel contains little spall material. A site in section 24, Shoreview, yielded samples averaging 0.1 percent shale and 0.6 percent iron oxide. A nearby site in section 25 contained 0.2 percent shale in the sand fraction, 0 percent in the gravel, and 0.4 percent iron oxide. A small amount of gravel may be available from ice-contact deposits in the southeast corner of Ramsey County.

SCOTT COUNTY

Most of the sand and gravel resources of Scott County lie within the broad terraces of the Minnesota River valley, along the northwest county boundary. Less voluminous deposits of ice-contact sands and gravels extend from the Minnesota River valley southeast into the interior of Scott County.

Burnsville Outwash (BVO): A small, narrow body of sand and gravel south of Savage, parallel to the Credit River, that was deposited during wastage of the Des Moines lobe. Parts of this deposit contain good sand and gravel; elsewhere the deposit is thin or contains an excess amount of sand or clay. Little subsurface information is available.

Credit River Ice-Contact Deposits (CRI): A series of discontinuous deposits parallel to the drainage of the Credit River. These deposits are probably collapsed sediment from a supraglacial stream which drained to the north, out onto the Burnsville outwash plain south of Savage. Little subsurface information is available, but most of these deposits appear to be gravel-poor.

Des Moines Ice-Contact Deposits (DEI, DMI): Sand and gravel deposits present throughout the county, that were laid down near or on top of the Des Moines-lobe ice. Many of these deposits are found near the eastern border of Scott County, and are associated with the terminal moraine of the Des Moines lobe. Meltwater within and on top of the stagnating ice deposited sand and gravel; these streams flowed east to the large outwash plains of Dakota County. Deposits are typically small and quite variable. Most of the deposits lie within areas of complex topography which, in combination with a lack of subsurface information, makes them difficult to interpret and evaluate.

Samples and notes from test borings in three locations in southeastern New Market Township illustrate the variability of these deposits. A pit in section 25 contains abundant crushing material (more than 1.25 inches, with about 5 percent boulders 8 to 24 inches in diameter). The deposit is not well sorted, and lacks intermediate-size pebbles. A site in section 35 provided a variety of results, some borings encounter thick gravel, others thick sand. Clay is also present, as well as boulders 1 to 2 feet in diameter. Spall content is only 0.5 percent. A nearby deposit in section 36 exhibits a wide range in shale content, averaging 3.5 percent, and a total spall content of 4.5 percent. This deposit contains less than 10 feet of gravel.

Other ice-contact deposits are present within the uplands above the Minnesota River valley. Sand and gravel were laid down here when meltwater within and on top of a stagnating ice sheet drained into the Mississippi River valley. Although these deposits contain thick beds of coarse gravel, the gravel has a high proportion of shale. Samples from a pit in section 20 of Sand Creek Township average 16 percent shale and provide a total spall of about 18 percent. Gravel from a pit in section 28 averages 13 percent shale.

A fairly large kame occupies most of section 26 in Spring Lake Township, and may (according to a few water wells), contain large amounts of sand and gravel. Samples from a deposit to the southeast of this kame, near Lake McMahon, contain 4 percent shale and a total spall of 5 percent.

Grey Cloud Terrace (GRT): Lower-level terrace along the Minnesota River. Most of the deposits that form the Grey Cloud terrace in Scott County are gravel-poor, or too thin to mine efficiently. Exceptions are a deposit southeast of Chaska, in which there is a large gravel pit, and a deposit northeast of Jordan in section 8. The deposit southeast of Chaska probably contains a substantial reserve of gravel. In the deposit near Jordan, bore holes and water wells indicate that about 10 feet of sand overlie thick gravel beds. Samples from this deposit include 0.5 percent spall. Nearly 5 million tons of aggregate are estimated to be available from these deposits.

Lakeville Outwash (LVO): Discussed under Dakota County.

Langdon Terrace (LGT): Middle-level terrace along the Minnesota River. Several large pits southwest and south of Shakopee have been opened in the deposits of the Langdon terrace. Samples from a pit in the southeast corner of section 16, Louisville Township, average 1.3 percent spall. Shale content was said to increase toward the base of the deposit. A pit just to the north in the same section provides about the same percentage of spall. Little subsurface information is available for parts of the terrace here, some of which is apparently underlain by sand or clay.

Another large deposit of Langdon terrace material is present in eastern Shakopee. The terrace here consists of sand and gravel that is estimated to be as thick as 60 feet. A large pit in section 16 exposes a sharp contact at a depth of about 20 feet. Above the contact, the sand and gravel contains a little shale (0.8 percent shale and a total spall of 1.5 percent). Below the contact the sand and gravel appears to be of Superior provenance, and contains virtually no shale (0.1 percent total spall). Samples from a small pit in section 14 yielded less than 1 percent spall materials.

A smaller deposit of Langdon terrace material lies south of Savage. The sand and gravel here is of a "uniform character... containing an exceptionally high percentage of metal." The gravel grades into sand south of the county road. Samples from pits in this deposit ranged from 1 percent to 3 percent spall.

A large deposit northwest of Jordan is not of such high quality. It is composed mostly of sand, but contains pockets of sand and gravel that range from 10 to 20 feet thick. Spall content in one pit is about 1 percent. A large gravel pit has been opened in a smaller deposit at Langdon terrace level southwest of Jordan in section 26. Significant amounts of sand and gravel apparently remain to be extracted here.

Prior Lake Ice-Contact Deposits (PRI): A group of more or less continuous sand and gravel deposits that trends northeast from Prior Lake. These deposits were laid down by both subglacial and supraglacial meltwater streams that flowed north toward Savage during wastage of the Des Moines lobe. A number of pits have been opened in this deposit, several yielding samples with less than 1 percent spall. Much of the deposit has been built over, and not many areas of good sand and gravel remain accessible. Very thick sections of sand and gravel occur locally within the deposit. These thick accumulations probably represent several episodes of deposition in the area, including deposition by the Superior lobe. Clay content varies widely, as does gravel content and size.

Richfield Terrace (RFT): Upper-level terrace along the Minnesota River. One large deposit of sand and gravel at this terrace level lies within the City of Shakopee. Although subsurface information is scarce, indications are that this deposit is made up of thick sand and gravel with moderate amounts of shale. A number of large gravel pits have been opened within the terrace in a deposit immediately southwest of Jordan. In a pit in the southwest corner of section 26, from 3 to 5 feet of cover overlie more than 30 feet of sand and gravel. A few boulders and cobbles are present, and shale is rare. In the southeast corner of the same section, a pit exposes about 25 feet of cobbly sand and gravel. Samples from borings in coarse gravel near this pit contained about 3 percent spall.

A large pit in section 25 exposes as much as 4 feet of cover that overlies 50 feet of mostly well-graded, very coarse sand and gravel, with thin silt beds towards the top. Cobbles are less than 8 inches, and most are between 2 and 6 inches in diameter. Carbonate rocks compose more than 30 percent, and shale about 2 percent of the pebble population, although much higher proportions are recorded in some individual beds. Total spall is about 3 percent. In section 19, over 50 feet of sand and gravel is exposed. All the gravel is less than 6 inches in size, and most is less than 4. Cover is less than a foot, but some clay seams are present within the deposit. A pit to the south in section 30 contains well-sorted gravel that includes 2 percent 8- to 16-inch clasts scattered throughout. Total spall is about 2.5 percent.

A large deposit of Richfield terrace material is near the town of Belle Plaine. Most of this deposit, however, consists of more than 20 feet of sand that overlies sand and gravel. The best places to mine sand and gravel within the deposit are the steep sides of gullies which have cut through the terrace. Most of the broad, flat areas contain little gravel in the upper portion. A pit opened in section 11 mines mostly sand, and has a spall content of about 3.5 percent. Clean, well-graded gravel that contains more than 4 percent spall has been mined from a pit in the southwest corner of section 3. The percentage of shale, however, is quite variable across the deposit. The operator of a 50-plus foot deep pit in section 2 reports a total spall content of less than 0.5 percent. A sample from a nearby shallow boring contained 0.5 percent shale and a total spall percent of 0.8. A good deposit to the east of Belle Plaine in section 33, St. Lawrence Township, has also been mined. One test hole here penetrated over 50 feet of gravel; water is encountered at depths between 30 and 35 feet. Spall content was only about 0.5 percent.

Sand Creek Ice-Contact Deposits (SCI): A series of discontinuous sand and gravel deposits associated with Sand Creek and its tributary, Raven Stream. These deposits were probably laid down by meltwater streams that flowed over or within the stagnating ice of the Des Moines lobe. The streams coalesced and flowed northwest into the Minnesota River valley at Jordan. These sands and gravels are less than 20 feet thick, and are probably less than 10 feet thick in most places. Despite their limited extent, several pits have been opened in these deposits, because they are the only source of gravel in south-central Scott County. Most of these pits are mined out, and most of the thick gravel deposits have probably already been identified.

A pit near Union Hill exposes heterogeneous, fine sand and fine gravel that contains shale. In section 18, Helena Township, a pit exposes a maximum of 16 feet of sand and gravel over clay, with an average thickness of less than 10 feet. A pit in section 17 shows sand and gravel at variable depths above clay, and encounters water at an average depth of 12 feet. The deposit is well graded with about 3 percent of the gravel over 1.25 inches in size and nothing over 5 inches, but the deposit is nearly depleted. A deposit south of Cedar Lake in section 25 is described as being of poor quality with considerable amounts of shale and clay lenses throughout. Samples from a deposit in section 34, Sand Creek Township, yield 11 percent shale, with a total spall content of over 12 percent.

Sand Creek Valley Fill (SCV): Sand and gravel terraces above Sand Creek. These deposits are small and, for the most part, are not volumetrically significant deposits. Little subsurface information was available to assess their potential.

WASHINGTON COUNTY

Several outwash deposits cover large areas of Washington County. Most of these were laid down by Superior-lobe meltwater. Terraces at several different levels along the St. Croix River also include extensive sand and gravel deposits. In all likelihood, the majority of these deposits will not continue to be available for mining because of competing land-use pressures.

Afton Valley Fill (AFV): Colluvial material which fills in lower-lying areas within the bedrock uplands in southeastern Washington County. We interpret most of these deposits to be thin and gravel-poor.

Big Marine Outwash (BMO): Collapsed outwash laid down by meltwater that issued from the Grantsburg sublobe. The deposit grades into ice-contact deposits at the eastern end of Forest Lake. Meltwater that flowed parallel to the terminal edge of the Grantsburg sublobe deposited sand and gravel from section 22 in Hugo all the way to Big Marine Lake. Here streams from the Forest Lake area joined it in flowing southeast through a channel cut into the May outwash to the St. Croix River valley. Large, stagnant ice blocks (left by the Superior lobe) underneath the outwash then collapsed, creating depressions within the deposit. In the process, lakes formed on the sand and gravel, and a fine sand or clay cover of varying thickness was deposited. The best gravel deposits were laid down at the heads of the meltwater streams.

Three pits in sections 22 and 23, Hugo, yielded samples that average 1.5 percent spall, most of which is shale. Two other pits in the area yielded samples that average 1 percent spall, again mostly shale. Three sites in section 19, New Scandia Township, average 0.5 percent shale and 0.3 percent iron oxide. A site in the southwest corner of section 18 yielded samples that average 0.6 percent shale and 0.3 percent iron oxide. Much of the deposit appears to be gravel poor or have thick overburden, or both.

Cottage Grove Outwash (CGO): An extensive deposit of sand and gravel laid down by meltwater that issued from the St. Croix moraine during the recession of the Superior lobe. The outwash was deposited at the same time as the Rosemount outwash in Dakota County. The Cottage Grove outwash consists of several valley trains that originate in the Lake Elmo quadrangle, and which coalesce within the City of Cottage Grove. Thickness of the deposit varies in part due to the irregularity of the older topography that it was laid down on, and in part due to the burial and subsequent melting of ice blocks. Soil above the sand and gravel is generally 2 to 3 feet thick.

While the texture of the outwash is variable, the clast lithology is generally uniform, consisting of granite, basalt, red felsite and red sandstone, all derived from the Lake Superior area, together with locally-derived limestone and dolostone. The percentage of limestone and dolostone ranges from rare to abundant. Exposures at different locations indicate a general fining-upward trend, from boulder and cobble gravel to finer gravel and coarse sand, although every section contains interbeds that display varied textures. Clasts are mostly subrounded to well rounded (Matsch, 1962, p. 25). Samples from five sites scattered across the deposit contain only a trace of shale and an average of 0.2 percent iron oxide. A number of gravel pits have been opened in the Woodbury area, but the deposit is rapidly being built over.

A highly collapsed portion of the outwash overlies a bedrock valley that trends southeast from section 31, Woodbury, to section 8, Cottage Grove. Texture is quite variable within these deposits, which probably include sediment laid down under, within, and on top of melting ice. Locally derived limestone and dolomite are abundant everywhere (Matsch, 1962, p. 27). Data from several pits within the deposit indicate only a slight trace of shale, 0.3 percent iron oxide, and no unsound chert.

Denmark Upland Gravel (DMU): Patches of older (pre-Late Wisconsinan) Superior-provenance sand and gravel left as erosional remnants above an elevation of about 900 feet. They are probably equivalent to deposits of the Hampton moraine in Dakota County. The deposits are chiefly pebbly to cobbly coarse sand. Rock types are similar to those in the Cottage Grove outwash, but clasts of northwest-provenance rock types are present in small amounts. Carbonate clasts are leached to a depth of 1 to 10 feet. Below the zone of leaching, local limestone and dolomite clasts are abundant. Thickness is variable, and unknown for most of the deposits (Matsch, 1962, p. 20). Deposits in sections 10, 11, and 15, Denmark Township, may contain significant amounts of gravel. A few other deposits may also be potential aggregate resources, but subsurface data are lacking.

Fish Lake Esker (FLE): A narrow, southeast-trending ridge north of Big Marine Lake, deposited by a subglacial meltwater stream beneath the Superior lobe. A few water wells in the deposit penetrate over 50 feet of gravel, but indications are that the overburden is fairly thick. A deep pit in section 7, New Scandia, shows overburden as thick as 10 feet or more. A pit in the esker in section 17 yields samples that contain only a trace of shale and 0.1 percent iron oxide.

Grantsburg Ice-Contact Deposits (GBI): Sand and gravel deposits laid down beneath or at the edge of the Grantsburg sublobe. They are associated with its terminal moraine, which cuts across the northwest part of Washington County. Ice-contact deposits at the edge of the moraine grade into Big Marine outwash. Some of these deposits contain thick sand and gravel. Samples from a site in section 13, Forest Lake, at the boundary of ice-contact and outwash deposits, average 0.5 percent shale and 0.8 percent iron oxide. Most of the isolated kames set back from the outwash generally contain less than 10 feet of gravel. Small pits have been opened in some of these deposits.

Grey Cloud Terrace (GCT): A lower-level terrace along the Mississippi and St. Croix rivers. A gravel pit on Lower Grey Cloud Island exposes about 50 feet of pebbly to bouldery stratified gravel and coarse sand, that is overlain by 1 to 5 feet of fine sand and silt. Current dredging operations are mining material more than 80 feet below the terrace surface. Much of the terrace deposit north of the island is less than 20 feet thick over dolomitic bedrock. Limestone, dolomite, and granitic rocks are abundant in the gravel. The red rocks of the Lake Superior basin are present, but not as abundant as in the Cottage Grove outwash. Shale is rare (Matsch, 1962, p. 31).

In the bluffs of the St. Croix River, sand and gravel of the Grey Cloud terrace level extends over a large area between the I-94 freeway bridge and Afton. The deposit is quite thick, contains at least 40 feet (and locally more than 100 feet) of sand and gravel. A pit opened in the northern part of the terrace was noted to be in “good gravel,” but was “considerably finer” than gravel in the higher-level terrace deposit (Langdon terrace). However, a pit opened at the southern edge of the terrace was in “good crushing gravel.” Samples from the latter pit were noted to contain 0.2 percent shale and 0.1 percent unsound chert. Most, if not all, of the deposit is not available for mining. Deposits at the Grey Cloud terrace level in Stillwater and Bayport are also built over. Based on a few well logs and exposures, the area mapped as Grey Cloud terrace in May Township probably contains coarse gravel.

Lake Elmo Outwash (LEO): A large body of sand and gravel deposited by meltwater streams that drained the Superior lobe. A plain about 2.5 miles wide in southern West Lakeland and northern Afton Townships was fed by streams that flowed from the north, northwest, and southwest, and coalesced to flow into the St. Croix River valley. Sand and gravel within this plain is commonly thicker than 40 feet and is usually covered by less than 5 feet of overburden. The outwash deposits that extend back from the plain generally do not seem to be of the same high quality.

The outlying outwash deposits can be divided into two types. The first type is present to the west of the main body of outwash, where sediments were deposited on top of the stagnating ice of the Superior lobe. The surface of this deposit is dotted by numerous closed depressions. Where these sediments fill steep bedrock valleys, sand and gravel is over 100 feet thick. Elsewhere, sand and gravel forms a thin veneer over till, or is interbedded with till. The second type of outwash (north of the main body of outwash) was deposited between stagnating ice blocks. These deposits have a smoother surface because fewer ice blocks melted beneath them. They also tend to be “perched” above the surrounding terrain, as the ice forming the walls of the valley in which they were deposited has long since melted. This second type of outwash may also have once included lakes, in which silt and clay were deposited above the coarser sediment left by the meltwater streams. This may explain the thick overburden which characterizes much of this deposit.

Only a small amount of spall is present in the Lake Elmo outwash. Samples from a site in section 5, Lake Elmo, yielded only a trace of shale with no iron oxide, as did samples from a site in section 9. Another site in the northeast corner of section 16, Lake Elmo yielded samples that contain a trace of shale and 0.3 percent iron oxide. A site north of Lake Jane in sections 3 and 4 yielded samples averaging a trace of shale and 0.4 percent iron oxide. Another site in the northeast corner of section 31 in Stillwater produced samples that contain only a trace of shale in the sand, and 0.4 percent iron oxide. A site near Horseshoe Lake in section 30 of West Lakeland Township included samples that contain 0.2 percent shale and no iron oxide. Samples from a site in section 33 provided no shale and 0.1 percent iron oxide. And finally, numerous samples from a site in section 4, Afton, averaged only a trace each of shale, iron oxide, unsound chert and other soft rock; 0.3 percent sandstone, and 40 percent limestone. The high amounts of locally-derived carbonate in this and surrounding pits leads to higher LAR values than are typical for Superior-lobe outwash. Quality apparently improves with depth.

Langdon Terrace (LDT, LGT): The middle-level terrace along the Mississippi and St. Croix rivers. Above the Mississippi River the deposits of the Langdon terrace consist of fine to coarse sand and gravel that is capped by fine sand and silt. Carbonate content is variable throughout the deposit, and shale is present mostly in the upper 10 feet, where it is mixed with the finer material. Samples from a site in section 17 in Cottage Grove contain about 0.5 percent shale and 0.3 percent iron oxide. A sample from a pit in section 30, about 10 to 25 feet below the top contains 0.1 percent shale and a total spall of 0.4 percent. A sample from a depth of about 8 to 12 feet in a test hole drilled in the southeast corner of section 28, contains 0.1 percent shale and 0.3 percent total spall.

Along the St. Croix River in the Lakeland area, numerous water wells penetrated more than 40 feet of sand and gravel at the Langdon terrace level. At least 30 feet of “heavy crushing gravel” was recorded to be available at a pit in section 35. The terrace in this area is nearly completely covered by housing developments. In the Bayport area, deposits of the Langdon terrace consist of more than 20 feet of sand and gravel, although some borings penetrated only about 10 feet of sand and gravel over thick sand. Overburden typically ranges from 1 to 5 feet thick. A number of gravel pits have been opened in this deposit, but it too is now almost completely built over. Other areas mapped at the Langdon terrace level along the St. Croix River are believed to be thick, coarse aggregate deposits, but are also not likely to be available for mining.

May Outwash (MYO): A very large body of outwash that forms a plain over much of May and Stillwater townships, extending from Stillwater to Marine on St. Croix. The outwash was laid down by meltwater that flowed to the east and southeast during the recession of the Superior lobe. A knob and kettle topography was created as buried stagnant ice melted and collapsed the overlying outwash. Big Carnelian Lake and Square Lake represent the former positions of large ice blocks within the outwash plain. Due to the disruption of the outwash, till is commonly interbedded with or at shallow depths beneath the sand and gravel deposits. Ponded water left thick silt and clay caps over sand and gravel in some areas, particularly to the west in Hugo and Grant townships, where the outwash grades into ice-contact deposits. These deposits may, in part at least, have been laid down beneath the ice sheet.

Although subsurface information is scarce across much of this broad plain, it indicates that sand and gravel is commonly greater than 50 feet thick. Where the outwash overlies buried bedrock valleys, water wells have penetrated as much as 150 feet of sand and gravel. Spall content is probably negligible throughout the deposit. A site in section 17 in Stillwater Township yielded samples that contained only a trace of shale and no iron oxide. A site to the north in section 1, May Township, produced samples containing only a trace of spall. Sites at the edge of the deposit in sections 25 and 26, Hugo, yielded samples that contained a trace of shale, iron oxide, and unsound chert; and 0.1 percent shale and no iron oxide, respectively. Two sites in sections 10 and 11 in Grant Township produced samples averaging only a trace of shale and 0.4 percent iron oxide.

Mississippi Floodplain (MSF): Recent alluvium deposited in the Mississippi River floodplain. In Washington County these deposits are restricted to a largely flooded area southeast of Lower Grey Cloud Island that is said by an aggregate company source to contain thick, coarse sand and gravel. Other such sites may be present within the floodplain of the Mississippi River, but most areas of gravel are probably overlain by thick, fine-grained river sediment.

Richfield Terrace (RHT): Upper-level terrace along the Mississippi and St. Croix rivers. Few data are available to evaluate the small area mapped at the Richfield terrace level above the Mississippi River in Washington County, but it is probably gravel-poor. In southeastern Washington County above the St. Croix River, deposits at the Richfield terrace level consist of less than 20 feet of sand and gravel over dolomitic bedrock. In places, however, deep, narrow, bedrock valleys have been filled by thick deposits of sand and gravel. One such deposit is in sections 10 and 15, Denmark Township. Another is in section 33 of Denmark Township. Test drilling at a site in section 15 penetrated more than 40 feet of gravel, and yielded samples containing only 0.2 percent shale, all of which is in the sand fraction, and 0.1 percent iron oxide. Borings at a site near a gravel pit in the southeast corner of section 15 yielded samples that average 0.2 percent shale, all in the sand fraction, 0 percent iron oxide, and 0.1 percent unsound chert. Borings in the pit floor yielded samples that contain only a trace of shale in the sand, no iron oxide and a slight trace of unsound chert.

A large remnant of the Richfield terrace is preserved between Stillwater and Afton. At its southern extent, sand and gravel were deposited over stagnant ice that lay in a bedrock valley. When the ice melted the sand and gravel collapsed, forming a “knob and kettle” topography of steep hills and depressions. Several large gravel pits have been opened, and indications are that deposits of the Richfield terrace consist of more than 50 feet of sand and gravel. Two adjacent sites in sections 22 and 23, West Lakeland Township, yielded samples that average less than 0.1 percent shale and 0.4 percent iron oxide; and 0.2 percent shale and 0.2 percent iron oxide, respectively. Percentage of spall throughout the deposit is probably similarly low. A DNR-Minerals study

(Ellingson, 1998) of an area near Bayport adjacent to a large gravel pit, records thick sand and gravel that contains no shale and an average of 0.4 percent total spall. Gravel percent was noted to decrease with depth at this site. Overburden is generally less than 3 feet thick. Well logs close to the edge of the terrace near Bayport indicate that sand and gravel is well over 100 feet thick.

In the northeast corner of Stillwater Township, the Richfield terrace surrounds an area of May outwash. Subsurface data indicate that terrace deposits here mostly consist of coarse sand and gravel, that are generally more than 50 feet thick, except in areas on the east and south sides where the gravel is thinner over dolomite bedrock. Samples from two sites in section 10 average 0.2 percent shale and 1.5 percent iron oxide, and 0.1 percent shale and 0.9 percent iron oxide. Smaller remnants of Richfield terrace deposits are present to the north in Marine on St. Croix and New Scandia townships. Here, the gravel that forms the terrace is generally 10 to 30 feet thick over bedrock. A pit in section 18 near the intersection of Minnesota Highways 95 and 97 produced samples that average 0.25 percent each of shale, iron oxide, and unsound chert.

St. Croix Outwash (SCO): Superior-lobe outwash deposits that are exposed in deep gullies cut through overlying deposits. These deposits are mapped in Stillwater and New Scandia townships. Available subsurface information indicates thick deposits of sand and gravel.

St. Mary’s Terrace (SMT): Lowest terrace level above the Mississippi and St. Croix rivers. Most deposits at this terrace level, although generally thick and coarse-grained, are probably not available for mining.

Superior Ice-Contact Deposits (SUI): These deposits consist of kames and eskers scattered throughout the central and northeast portions of Washington County. They were deposited by meltwater from the Superior lobe, which fed the various outwash plains associated with the Superior lobe. Many of these deposits are given a classification of 4, not necessarily because they are poor deposits, but because little or no subsurface data is available with which to assess them. Where water-well logs are available, especially in May Township, these ice-contact deposits are known to contain over 50 feet of sand and gravel. As with most ice-contact deposits, sand and gravel may be interbedded with till or overlain by thick overburden. Samples from a pit opened in a large ice-contact deposit in section 35 of New Scandia Township contained neither shale nor iron oxide.

Tower Kame (TOK): Prominent kame complex in sections 15, 16, and 17, in Woodbury, that was deposited at the edge of the St. Croix moraine as an alluvial fan at the head of the Cottage Grove outwash plain. The sand and gravel are probably interbedded with and overlain by sandy till. Almost no subsurface data are available to estimate aggregate volume. These deposits are not available for mining due to urbanization.

APPENDIX B

DESCRIPTION OF BEDROCK AGGREGATE RESOURCES

ANOKA COUNTY

There are no areas of Prairie du Chien dolostone accessible for mining in Anoka County. All areas where the Prairie du Chien is the “first bedrock” below the land surface are buried by overburden that is generally more than 100 feet thick.

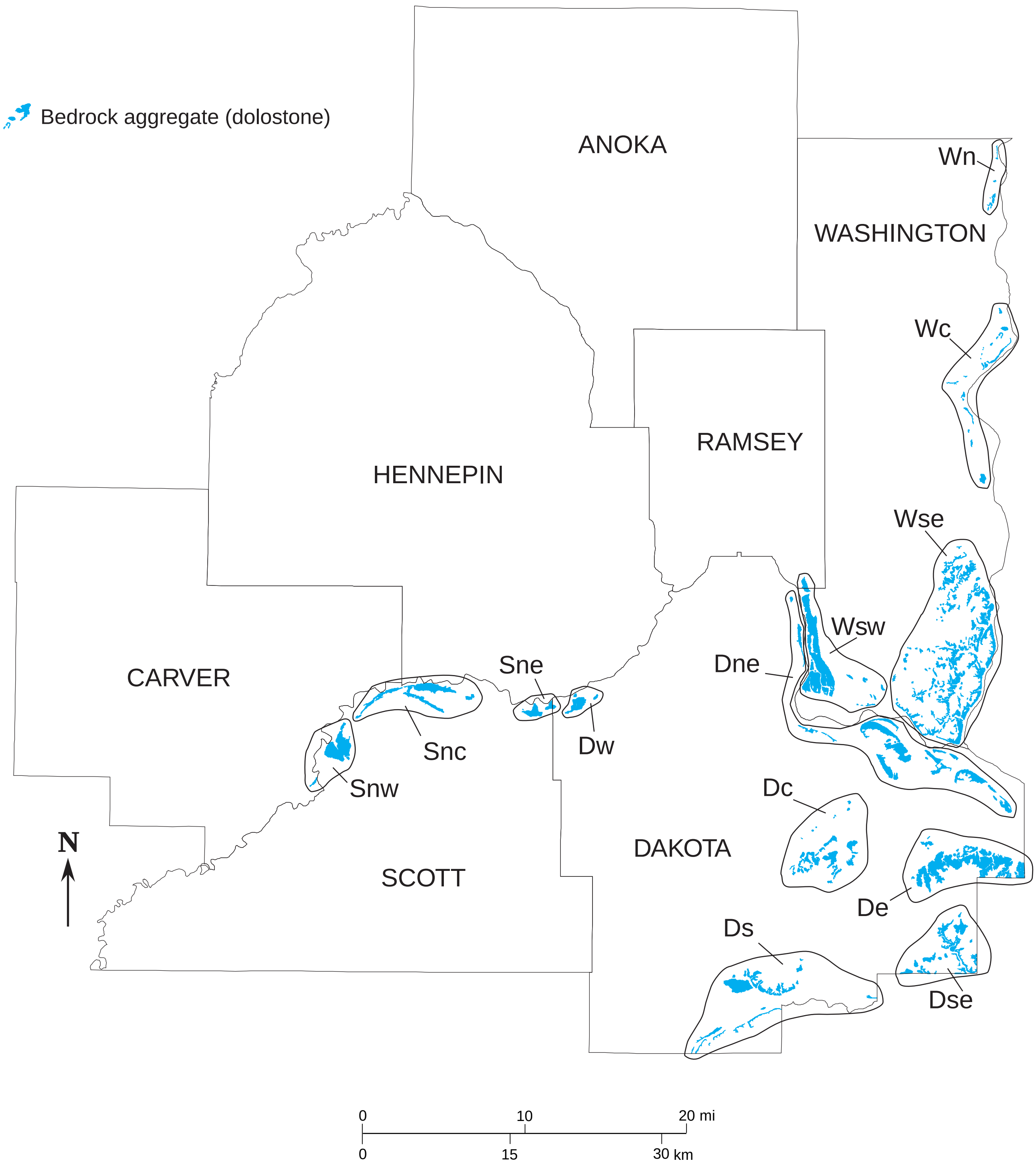
CARVER COUNTY

A small area of Prairie du Chien dolostone is present in southeastern Carver County. Dolostone bedrock in this area that is less than 10 feet thick is not included in the resource estimates. As with many of the thin deposits, the Prairie du Chien here could be used if a nearby market were found that needed a very limited supply of bedrock aggregate. In the remainder of Carver County, dolostone bedrock is either not present, or is overlain by glacial sediments that are generally more than 200–300 feet thick.

DAKOTA COUNTY

Major exposures of Prairie du Chien dolostone are along and just inland of the Mississippi River. They extend from south of Grey Cloud Island to the extreme southeastern part of Dakota County. Some areas of exposed or shallowly buried Prairie du Chien bedrock extend in toward the center of Dakota County. The Prairie du Chien is particularly well exposed in and along tributary drainageways to the Mississippi, including the Cannon River in the southern part of Dakota County. Prairie du Chien bedrock is also present in extreme eastern Dakota County about 5 miles southeast of Hastings. Areas that are inaccessible due to land-use considerations include those near the municipalities of Hastings, Waterford, and Cannon Falls, the wild and scenic river area adjacent to the Cannon River, the Mississippi River northwest of Hastings, as well as scattered areas in the southeastern portion of Dakota County that include housing developments and farmsteads.

(1) <u>Dakota west (subregion Dw)</u>. Prairie du Chien dolostone is present along a terrace of the Minnesota River. A large quarry is currently operating in this area and much of the resource has been depleted. The mapping done for this study does not indicate the presence of any additional resources.



Appendix Figure B-1. Subareas of bedrock aggregate resources discussed in Appendix B. The symbols pertain to generalized geographic portions of Scott (S), Dakota (D), and Washington (W) counties.

(2) Dakota northeast (subregion Dne). The exposures and near-surface presence of Prairie du Chien dolostone in this subregion are the result of a slight structural uplift in eastern Dakota County that was incised by the Mississippi and Vermillion rivers. The Prairie du Chien ranges from 35-feet thick near the Mississippi River to 250-feet thick southwest of Hastings, away from the river. Because of the structural uplift and related faulting, thickness is quite variable and somewhat unpredictable, but thickness generally increases away from the Mississippi River. Several quarries have operated east and west of Hastings, and currently there is a large active quarry southwest of Hastings. There may be more potential resources than are shown in the earlier study (Meyer and Jirsa, 1984) along the terraces and bluffs on the Mississippi southeast of Hastings.

(3) Dakota central (subregion Dc). Prairie du Chien dolostone forms a plateau and ridge subregion southeast of Empire in central Dakota County. The Prairie du Chien in this subregion is approximately 140 to 240 feet thick. Many small quarries (shown on the aggregate map) have operated in this subregion in the past. Much of western part of the area is becoming unavailable because of ongoing residential development along U. S. Highway 52. Giddings soil-probe borings indicate that shallow bedrock is much more extensive in the eastern part of the subregion than shown in the earlier study by Meyer and Jirsa (1984).

(4) Dakota east (subregion De). Prairie du Chien bedrock in this area forms low, east-west trending bluffs that extend from extreme eastern Dakota County westward into south-central Dakota County. Exposures are present along a small structural uplift in eastern Dakota County. The dolostone extends southward from the bluffs where it crops out. Southward from the bluffs, the dolostone is mantled by glacial sediments that thicken progressively toward the south. In some places the younger Paleozoic formations that overlie the Prairie du Chien (such as the St. Peter Sandstone) are present. Estimates of the amount of this resource are only moderately reliable in the western part of this subregion because of the sparse distribution of water-well and soil-boring information. However, newly acquired Giddings soil-probe borings confirm the thickness of overlying glacial sediments, and the depth to bedrock in areas where bedrock outcrops are lacking. Water-well data indicate that the Prairie du Chien ranges from 220 to 280 feet thick in the western end of the subregion. There is one active quarry at the western end of the subregion and a small inactive quarry at the eastern end. Data for mapping and resource evaluation are plentiful in the eastern part of the region along State Highway 316, but rapid urbanization is making most of that area unavailable for quarrying.

(5) Dakota southeast (subregion Dse). Prairie du Chien bedrock is present along a tributary stream to the Cannon River in the extreme southeastern part of Dakota County. The dolostone is exposed along river bluffs, and continues back from the bluffs, where it is covered with more than 10 feet of glacial sediment. Giddings soil-probe data and data from water-well records indicate extensive areas where Prairie du Chien dolostone is less than 10 feet below the surface of the plateau that extends to the west and to the northeast of the valley. The Prairie du Chien is more 300 feet thick in some water wells in this area. Because subsurface data are limited, resource estimates for southeastern Dakota County may be conservative.

(6) Dakota south (subregion Ds). The Prairie du Chien dolostone forms a terrace and low bluffs along the Cannon River in the southernmost part of Dakota County. A quarry used to operate in the westernmost part of this subregion. The Prairie du Chien Group is as thick as 250 feet in this subregion.

HENNEPIN COUNTY

There are no bedrock aggregate resources in Hennepin County.

RAMSEY COUNTY

There is a small area of Prairie du Chien bedrock present next to the Mississippi River in southeastern Ramsey County; however, it is in a highly urbanized area and is unavailable.

SCOTT COUNTY

Prairie du Chien dolostone is close to the present land surface along the Minnesota River terrace in the northern part of Scott County. Along much of this terrace, bedrock is covered by 20–30-foot-thick deposits of sand and gravel. Therefore, more bedrock resources might become available if the sand and gravel were removed. Much of the area is urbanized. Bedrock aggregate resources in Scott County can be divided into the three subregions described below:

(1) Scott northwest (subregion Snw). Prairie du Chien dolostone underlies the Minnesota River terrace in northwestern Scott County. In this subregion, the dolostone is comparatively thin (50 to 85 feet), and is underlain at shallow depths by the Jordan Sandstone. Several large quarries have operated or are currently operating in the Prairie du Chien in this subregion, and much of the resource is already mined.

(2) Scott north-central (subregion Snc). Prairie du Chien dolostone underlies the terrace south of the Minnesota River and ranges from 70 to 90 feet thick. Most of the area has not been quarried because it is an area of urban development (City of Shakopee). There are, however, active or recently active quarries in the less developed areas at either end of the subregion.

(3) Scott northeast (subregion Sne). Prairie du Chien bedrock in this subregion in northeastern Scott County also underlies a terrace of the Minnesota River. Most of the remaining resource is present at the margins of two quarries that have been stripped free of overburden. The overburden was apparently thicker than 10 feet over most of the area prior to mining. These quarries are being encroached upon by urban development.

WASHINGTON COUNTY

Most of the bedrock aggregate resources in Washington County are unavailable because they underlie municipalities (Stillwater, St. Paul suburbs) or recreational land along the St. Croix River. The major exposures or areas where Prairie du Chien bedrock is buried by less than 10 feet of overburden are along the bluffs of the St. Croix River in the northern part of the county, and in the widespread bluffs, ridges, and plateaus to the south, both along and inland from the St. Croix and Mississippi rivers and their tributaries. The major resource subregions are described below:

(1) Washington north (subregion Wn). In extreme northeastern Washington County the Prairie du Chien is exposed in steep bluffs adjacent to the St. Croix River. It extends westward, but becomes covered by a thick sequence of glacial sediments only a short distance inland from the bluffs. Mining of these resources would be extremely difficult because of the steep slopes, and their proximity to recreational land along a scenic waterway.

(2) Washington central (subregion Wc). In central Washington County, in the vicinity of Stillwater, most Prairie du Chien bedrock exposures are in the terrace bluffs along the St. Croix River, and on ridges immediately west of the terraces. The dolostone generally ranges from 30 to 80 feet thick, but thickens to more than 100 feet at the southern extent of the subregion. Most of the areas in this subregion in which bedrock is less than 10 feet below the land surface are comparatively small (50 to 100 acres) relative to other subregions. Quarries currently operate in both the northern and southern parts of this subregion. Dolostone has also been quarried in and near Stillwater and Bayport, but those activities have ceased.

(3) Washington southeast (subregion Wse). Bedrock of the Prairie du Chien Group is widely exposed in the southeast part of Washington County. The dolostone forms bluffs along the St. Croix and Mississippi rivers and their tributary streams, and is present on ridges and plateaus inland. The location and extent of these bedrock outcrops is controlled by the Hudson-Afton anticline. In southeastern Washington County, the Prairie du Chien varies greatly in its thickness. Along the crest of Hudson-Afton anticline in the northern part of the subregion the Prairie du Chien is commonly less than 30 feet thick, and further north along the crest of the anticline it is absent. In the southern part of this subregion the dolostone may range in thickness to as much as 270 feet, although thickness is variable because of faulting related to the Hudson-Afton anticline. Most outcrops and areas of shallow Prairie du Chien bedrock (<10 feet overburden) are along bluffs on the St. Croix and tributary streams. New well logs and soil borings indicate that overburden thicknesses increase rapidly behind the bluffs and therefore the earlier study by Meyer and Jirsa (1984) was overly generous in assigning areas of shallow bedrock.

(4) Washington southwest (subregion Wsw). Prairie du Chien bedrock is present in a low terrace of the Mississippi River in southwest Washington County. The Prairie du Chien ranges from 120 to 170 feet thick in this subregion. Groundwater levels, which are probably about the same as the river elevation, limit the depth of quarrying. This subregion contains a major active quarry on upper Grey Cloud Island. There are also several small inactive quarries to the north and east.

APPENDIX C

SUMMARY OF PHYSICAL AND CHEMICAL TEST DATA

Introduction

This appendix furnishes sets of physical and chemical test data for natural and bedrock aggregates to illustrate the salient characteristics of the materials. More comprehensive test data may be obtained from the primary sources listed here. We emphasize that most of the test results presented here are from tests performed on beneficiated (processed) aggregate. Processing, by means of blending and sorting, can severely alter the composition of aggregate and, therefore, the test results may not be representative of material from an entire pit or quarry. In many cases, test results are a better indication of the processing method than of the quality of the original material. In addition, the material tested in even the most recent of these tests is probably no longer present in the pit or quarry from which it originally came. Although aggregate of comparable quality may be obtainable, the test indicates only the characteristics of aggregate produced in the past. It also should be noted that analytical tests are not always a reliable and complete indication of the performance of the aggregate.

Natural Aggregate (Sand and Gravel) Test Results

Los Angeles Rattler (LAR) test results for sand and gravel aggregate are summarized in Table C-1. The LAR is a standard method for testing the resistance to abrasion of aggregate (AASHTO test T 96, ASTM test C 131). Coarse aggregate is tumbled in a steel cylinder for a specified time. The percentage of fine material that is abraded from the aggregate in relation to the amount of coarse aggregate originally placed in the cylinder is the LAR loss percent. The more resistant the aggregate, the smaller the LAR values.

Bedrock Aggregate (Dolostone) Test Results

The results of several commonly performed physical and chemical tests are summarized in Table C-2. The table shows the average and range (minimum and maximum), and the number of analyses used for each determination. The locations from which samples were taken for testing are described in Table C-3.

The following are brief descriptions of tests performed on bedrock:

Specific gravity: The ratio of weight of rock to weight of an equal volume of water—used to determine the weight of aggregate occupying a given solid volume or the volume occupied by a given weight (AASHTO test T 84, ASTM test C 127).

Density: The weight of the aggregate expressed in pounds per cubic foot.

Appendix Table C-1. Summary of Los Angeles rattler tests for natural aggregate (sand and gravel)

	Aggregate size range*			
Deposit (County and deposit name)	9.5–37.5 mm (0.375–1.5 in.)	9.5–19.0 mm (0.375–0.75 in.)	4.75–9.5 mm (0.20–0.375 in.)	**Number of pits sampled**
Anoka County	no test results available			
Carver County				
Crow River Outwash	27.1 (3)	29.8 (1)	26.5 (2)	3
Piersons Lake Ice Contact	25.4 (1)	-	-	1
Richfield Terrace	25.1 (1)	25.1 (6)	-	2
Dakota County				
Apple Valley Outwash	19.4 (8)	20.8 (8)	-	1
Burnsville Outwash	-	28.2 (1)	-	1
Cannon River Outwash	25.6 (10)	26.1 (15)	-	5
Des Moines Ice Contact	28.2 (1)	-	-	1
Hampton Moraine	24.1 (7)	24.3 (3)	26.6 (1)	3
Lakeville Outwash	22.0 (18)	23.0 (12)	25.6 (6)	4
Langdon Terrace	19.9 (7)	21.6 (7)	-	1
Rich Valley Train	19.6 (19)	19.4 (12)	-	2
Rosemount Outwash	21.1 (31)	20.4 (10)	18.9 (1)	9
Superior Ice Contact	25.1 (1)	21.4 (8)	-	4
Valley Delta Gravel	18.4 (2)	18.1 (3)	-	1
Vermillion River Outwash	19.5 (15)	20.2 (5)	22.2 (2)	2
Waterford Outwash	28.7 (8)	27.0 (5)	-	2
Hennepin County				
Bloomington Outwash	23.3 (8)	23.6 (9)	-	3
Crow River Outwash	23.6 (13)	24.7 (17)	23.8 (8)	8
Eden Prairie Outwash	27.4 (2)	27.6 (1)	-	1
Grantsburg Ice Contact	18.8 (1)	21.7 (3)	-	2
Grey Cloud Terrace	25.7 (4)	22.9 (10)	-	1
Langdon Terrace	22.9 (1)	26.2 (2)	-	1
Minneapolis Outwash	19.7 (11)	21.9 (8)	-	1
Osseo Kame	14.1 (40)	15.5 (35)	13.7 (1)	8
Ramsey County				
Arsenal Kame	15.9 (15)	17.6 (19)	-	1
North Oaks Ice Contact	25.6 (1)	-	-	1
Superior Ice Contact	13.6 (2)	15.7 (4)	-	2
Scott County				
Des Moines Ice Contact	22.3 (4)	26.1 (4)	25.9 (1)	4
Grey Cloud Terrace	20.9 (2)	24.4 (2)	-	1
† Langdon Terrace	23.5 (29)	23.2 (17)	-	6
Prior Lake Ice Contact	19.9 (5)	21.4 (2)	22.0 (2)	3
Richfield Terrace	24.0 (26)	24.2 (26)	-	5
Sand Creek Ice Contact	-	25.7 (1)	25.7 (2)	1
Washington County				
Big Marine Outwash	18.7 (29)	20.0 (41)	18.9 (14)	10
Cottage Grove Outwash	19.7 (13)	20.6 (8)	-	6
§ Lake Elmo Outwash	21.6 (37)	21.9 (31)	17.5 (3)	8
Langdon Terrace	-	21.7 (2)	-	1
May Outwash	17.7 (26)	18.9 (25)	17.6 (5)	8
Richfield Terrace	17.5 (31)	17.4 (21)	-	5
St. Mary's Terrace	16.8 (2)	-	-	1

* Numbers in parentheses indicate the number of tests on which the results are based.

† Deposits of the Langdon terrace in Scott County yielded samples with a wide range of values, from 16.9 to 30.6 for the 9.5–37.5 mm size range, and from 19.8 to 27.7 for the 9.5–19.0 mm size range. .

§ The Lake Elmo outwash yielded samples with a wide range of values, from 14.0 to 31.2 for the 9.5–37.5 mm size range, and from 14.5 to 32.0 for the 9.5–19.0 mm size range. The wide range in reported values is probably the result of local variations in the amount of limestone and dolostone clasts.

Appendix Table C–2. Physical and chemical tests, bedrock aggregate

LOCATION (see Appendix Table C-3)	SPECIFIC GRAVITY *				DENSITY lbs per cubic foot				ABSORPTION †				LAR TEST § % of loss				MgSO4 TEST ¶ % of fines lost				INSOLUBLE RESIDUE % by weight				Mg/Ca RATIO			
	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)	Avg	Min	Max	(No.)
DAKOTA COUNTY																												
D2	2.66	-	-	(1)	156	151	158	(5)	-	-	-	-	-	-	-	-	16	7	27	(61)	3.13	2.56	3.8	(2)	-	-	-	-
D3	2.73	-	-	(1)	171	-	-	(1)	0.84	-	-	(1)	-	-	-	-	-	-	-	-	3.26	-	-	(1)	0.51	-	-	(1)
D5	-	-	-	-	159	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HENNEPIN COUNTY																												
H1	-	-	-	-	157	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RAMSEY COUNTY																												
R4	-	-	-	-	160	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SCOTT COUNTY																												
S	-	-	-	-	154	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S1	2.64	-	-	(1)	-	-	-	-	2.1	-	-	(1)	23.1	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-
S2	2.66	-	-	(1)	-	-	-	-	1.6	-	-	(1)	33.7	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-
S3(b)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.36	2.00	8.00	(7)	0.55	0.52	0.59	(8)
S5	2.58	2.46	2.70	(6)	-	-	-	-	3.3	1.7	5.3	(6)	30.2	23.1	33.5	(3)	11	3	22	(39)	-	-	-	-	-	-	-	-
S6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.38	4.05	4.7	(2)	-	-	-	-
WASHINGTON COUNTY																												
W1(b)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W2	2.58	-	-	(1)	-	-	-	-	3.2	-	-	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W3	2.55	2.45	2.60	(3)	-	-	-	-	3.8	2.2	4.8	(3)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W4	2.46	2.35	2.51	(3)	-	-	-	-	4.5	3.6	5.8	(3)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W6	2.63	2.56	2.73	(45)	-	-	-	-	2.12	0.84	5.8	(46)	31.9	20.4	41.5	(50)	10	2	18	(58)	-	-	-	-	0.52	0.42	0.59	(4)
AVERAGE	2.61	2.35	2.73	(61)	158	151	160	(10)	2.4	0.84	5.8	(62)	31.7	20.4	41.5	(55)	-	-	-	-	4.66	2.00	8.00	(12)	0.53	0.42	0.59	(13)

* Specific gravity is the ratio of the mass of a body to the mass of an equal volume of water at 4^0 C (or other specified temperature)

† The amount of water that one unit volume of aggregate can absorb, expressed as percent of total weight

§ Los Angeles rattler test. A measure of the resistance to abrasion. Reported as percentage of loss, and represents the average for several sizes of aggregate

¶ A measure of the effects of repeated freezing and thawing of material. Reported as the percent of fine material lost

Appendix Table C–3. Locations of dolostone bedrock test samples
(test data reported in Appendix Table C–2)

Locality Number	Quarry Name	Quarry Status	Owner or Operator	Location
DAKOTA COUNTY				
D2	Burnsville Quarry	active	Ed. Kraemer and Sons, Inc.	T. 27 N., R. 24 W., sec. 33
D3	Hastings Crushed Stone Quarry	inactive		T. 115 N., R. 17 W., sec. 22
D5	Well (tested interval 50-65 feet)			T. 112 N., R. 18 W., sec. 12
HENNEPIN COUNTY				
H1	Well (tested interval 102.6-112.6 feet)			T. 119 N., R. 21 W., sec. 36
RAMSEY COUNTY				
R4	Well (tested interval 8.8-20.8 feet) on Harriet Island			T. 28 N., R. 22 W., sec. 6
SCOTT COUNTY				
S	Shakopee area			location not specified
S1	Landers Quarry	inactive	Acquired by Shiely, 1963	T 115 N., R. 22 W., sec. 2
S2	Landers Quarry	urbanized land		T. 115 N., R. 22 W., sec. 1
S3	J.B. Contre Quarry (Shakopee)	urbanized land		T. 115 N., R. 23 W., sec. 1
S4	Merriam Junction (near quarry)			T. 115 N., R. 23 W., sec. 29
S5	Merriam Quarry	inactive	Bryan Rock Products, Inc.	T. 115 N., R. 23 W., sec. 29
S6	Bryan Rock Products, Inc. (sample)			T. 115 N., R. 22 W., sec. unknown
WASHINGTON COUNTY				
W1	"Old" Quarry (near Soo line high bridge)	inactive		T. 31 N., R. 19 W., sec. 31
W2	Arcola Quarry	inactive	Bryan Rock Products Inc.	T. 31 N., R. 19 W., sec. 31
W3	Outcrop, St. Croix River bluff			T. 30 N., R. 20 W., sec. 11
W4	"Old" Quarry	urbanized land		T. 30 N., R. 20 W., sec. 20
W5	McNaughton Quarry (Stillwater)	urbanized land		T. 30 N., R. 20 W., sec. 34
W6	Larson *or* Von Der Weyer Quarry	active	Aggregate Industries, Inc.	T. 27 N., R. 22 W., sec. 25

Absorption: The amount of water that one unit volume of the aggregate can absorb, expressed in percent of total weight. This is an approximate measure of the porosity and permeability of the aggregate (AASHTO test T 84, ASTM test C 127).

LAR (Los Angeles Rattler Test): A measure of resistance to abrasion as discussed in the section on sand and gravel above (p. 73). Values are expressed in percent loss and represent averages of several sizes of aggregate (AASHTO test T 96, ASTM test C 131).

Magnesium Sulfate (MgSO4) Test: Repeated cycles of immersion in magnesium sulfate and drying cause some rocks to weaken as salt crystals expand in pore spaces. The results are expressed as the percent of fine material lost. Larger numbers therefore generally indicate less sound material. The test is used to accelerate the expansion characteristics of repeated freezing and thawing of material (AASHTO test 104, ASTM test C 88).

Insoluble Residue: The material that remains after dissolution of a rock sample in hydrochloric acid. Residues typically consist of silica (sand, silt), chert, shale, and organic material. Some of these materials are considered deleterious for certain aggregate uses. The results are given in percent by weight.

Magnesium / Calcium ratio: Provided for general information only.

Other engineering test results that are available from the sources listed below include compressive strength, Poisson's ratio, shear modulus, tensile strength, velocities of longitudinal bar and pulse, Young's modulus, ultimate strength, and shore hardness. In addition, some chemical test data, including major element and oxide analyses are available, although they are not listed here. These data were not included because of their limited usefulness to this study.

Sources of Analytical Data and Testing Procedures

File data:

Minnesota Department of Transportation
Graham Ford (Geology and Aggregate)
Earling Christopher (Testing Lab.)
United States Army Corps of Engineers
Robert Whartman
U.S. Department of Interior, Bureau of Mines, Twin Cities Mining Research Center (now closed)

Published data and other references:

Emmons, W.H., and Grout, F.F., 1943, Minerals resources of Minnesota: Minnesota Geological Survey Bulletin 30, 149 p.

Parham, W.E., Inventory of bedrock analyses, Geology for urban planning—Twin City Metropolitan area: unpublished data filed at Minnesota Geological Survey.

Schenck, G.H.K., and Torries, T.F., 1975, Crushed stone, in Industrial Minerals and Rocks, 4th edition, S.J. Lefond, ed., American Institute of Mining, Metallurgical and Petroleum Engineers, p. 66-84.

Stauffer, C.R., 1950, The high magnesium dolomites and dolomitic limestones of Minnesota: Minnesota Geological Survey Summary Report no. 4. 29 p.

Stauffer, C.R., and Theil, G.A., 1933, The limestones and marls of Minnesota: Minnesota Geological Survey Bulletin 23, 193 p.

APPENDIX D

AGGREGATE RESOURCES MAPPING METHODOLOGY

Digital maps that show the extent of bedrock aggregate (dolostone) and natural aggregate (sand and gravel) resources were produced by the Minnesota Geological Survey using ARCVIEW, a geographic information system software package. In order to determine the areas of bedrock aggregate and natural aggregate that are encumbered by urbanization, the resource maps were digitally overlain by the digital land-use maps prepared by the Metropolitan Council for 1984, 1990 and 1997 (Metropolitan Council, 1997, and Metropolitan Council unpublished data, 1999). The digital land use maps were prepared by digitizing land use from aerial photos.

The following land-use categories together constitute urbanized areas, and are deemed to encumber aggregate resources when the footprint of these land uses overlies an aggregate resource:

Single-family residential development

Multi-family residential development

Commercial development

Industrial development

Public and semi-public facilities (schools, hospitals, churches, nursing homes, cemeteries, ice arenas and all facilities of local, states and federal governments).

Public Industrial (publicly-owned areas such as wastewater treatment plants, transit bus garages Minnesota Department of Transportation's sand and salt storage facilities, etc.).

Airports

Parks and recreation areas

Streets and roadways

Gravel pits and quarries

Because local regulations usually require mining operations to maintain some distance from residential development and streets and highways, a 200-foot-wide buffer was created around development and a 100-foot-wide buffer was created on each side of streets or roads shown in The Lawrence Group Street Centerline File (Lawrence Group. 1999). Digital theme maps of these areas were created and the buffered areas were then withdrawn from areas that were considered available for mining.

Industrial Parks that are not yet developed, as well as vacant land identified as public and semi-public (such as the arsenal site in Shoreview and the University of Minnesota property in Rosemount) were not included in the “urbanized land”. Aggregate deposits, if any, that underlie these areas were determined to be available for mining.

Digital maps of areas projected to be urbanized in 2020 and 2040 were prepared by adding to the 1997 urbanization map (as defined above) the areas that the Metropolitan Council has designated for future metropolitan urban services for 2020 and 2040 (Metropolitan Council, 1996). The 2020 and 2040 Metropolitan Urban Service Areas (MUSA) are preliminary and tentative. The ultimate boundaries of the 2020 MUSA are yet to be determined by the 189 cities and townships in the seven-county metropolitan area as part of their local comprehensive planning process. These plans are prepared by the local cities and towns and reviewed and approved by the Metropolitan Council as provided under the 1976 Metropolitan Land Planning Act and subsequent amendments.

The 2040 boundaries are more speculative because of the 40-year time span. They include the areas that the Metropolitan Council has determined will be necessary to accommodate the forecasted growth in population, housing and employment through 2040. Any one of many factors such as changes in the growth rate of the economy, unexpected in-migration from regions afflicted by armed conflicts or other areas, and increases or decreases in the density of development could dramatically change the amount of land that will be required.

The requirements of environmentally sensitive areas were also included in calculations of the future availability of aggregate resources. Digital maps were created or obtained for the following areas:

(1) Streams and rivers, with the area covered by them being augmented by a 200-ft-wide buffer along their banks.

(2) Wetlands that are 5 acres or more in size. They include a 100-ft-wide buffer around them.

(3) Scientific, natural and wildlife areas owned and managed by the Minnesota Department of Natural Resources.

(4) Open water bodies, which include a 100-ft-wide buffer.

These areas were determined to be unavailable for the mining of any aggregate resources that underlie them. It should be noted that areas owned by environment or conservation-oriented groups such as Nature Conservancy, Audubon Society, Minnesota Land Trust, Trust For Public Land, or easements held by these organizations were not removed from the areas which could be mined. Specific geographic information on those land holdings or easements was not available. Thus it is not possible to determine the quantity of aggregate, if any, that is encumbered in these sites. Any aggregate resources located in those areas will be unavailable for extraction.

APPENDIX E

METHODOLOGY FOR DETERMINING DEPLETION OF AGGREGATE RESOURCES

1. Digital overlays of urban areas for 1997, 2020, and 2040 were used in conjunction with the digital map of the bedrock and natural aggregate deposits to determine which aggregate resources would become urbanized.

2. The amount of aggregate encumbered, and therefore unavailable in 2020 and 2040 because of urbanization, was then calculated.

3. The amount of aggregate encumbered by urbanization was then divided by the number of years to determine an annual rate of depletion.

4. The annual demand for aggregate was forecasted using a simple regression analysis of historical demand and extending the trend line(s) to 2040 (Appendix Table E-1). Several variables were looked at to determine whether there was a correlation between them and the amount of aggregate used. The best fit was determined from a regression analysis of aggregate demand and total population (Tables 7 and 8). Because of a sharp increase in the aggregate demand during the 1990-1998 period, it was decided to use two trend lines (1950–1998 and 1990–1998) to forecast the demand through 2040.

5. The annual rate of aggregate depletion due to urbanization was then added to each of the two forecasted annual demand scenarios to obtain an annual depletion rate. This annual depletion rate was then deducted from the resources available to arrive at two scenarios for an estimated date when the resources would no longer be available (2029 and 2034).

Recycling of material is visible at major transportation project sites throughout the metropolitan area. Unfortunately no figures are readily available to identify a historical trend. As a result, no attempt was made to project future recycling or quantify the benefits of recycling in preservation of aggregate resources.

Appendix Table E–1. Numerical results of aggregate-demand and cumulative-depletion calculations (in tons), based on (1) 1950–1998 trends, and (2) 1990–1998 trends.

Year	Depletion through urbanization (80-acre parcels basis)	Annual aggregate demand 1950–1998 scenario	Cumulative depletion (urbanization plus demand based on 1950–1998 trend)	Annual aggregate demand as 1990–1998 scenario	Cumulative depletion (urbanization plus demand based on 1990–1998 trend)
1997	1700030708		1700030708		1700030708
1998	1686255780	24767416	1661488364	26950705	1659305075
1999	1672480852	25245446	1622467990	27902607	1617627540
2000	1658705924	25723494	1582969568	28854542	1574998070
2001	1644930996	26097444	1543097196	29599189	1531623954
2002	1631156068	26471394	1502850874	30343835	1487505191
2003	1617381140	26845345	1462230601	31088482	1442641781
2004	1603606212	27219295	1421236378	31833128	1397033725
2005	1589831284	27593245	1379868205	32577775	1350681022
2006	1576056356	27967195	1338126082	33322422	1303583672
2007	1562281428	28341146	1296010008	34067068	1255741676
2008	1548506500	28715096	1253519984	34811715	1207155033
2009	1534731572	29089046	1210656010	35556361	1157823743
2010	1520956644	29462996	1167418086	36301008	1107747807
2011	1507181716	29836947	1123806211	37045655	1056927225
2012	1493406788	30210897	1079820386	37790301	1005361995
2013	1479631860	30584847	1035460611	38534948	953052119
2014	1465856932	30958797	990726886	39279595	899997597
2015	1452082004	31332748	945619210	40024241	846198428
2016	1438307076	31706698	900137584	40768888	791654612
2017	1424532148	32080648	854282008	41513534	736366149
2018	1410757220	32454599	808052481	42258181	680333040
2019	1396982292	32828549	761449004	43002828	623555285
2020	1383207364	33202499	714471577	43747474	566032882
2021	1369964542	33576449	667120200	44492121	507765833
2022	1356721720	33950400	619394872	45236768	448754138
2023	1343478898	34324350	571295595	45981414	388997796
2024	1330236076	34698300	522822367	46726061	328496807
2025	1316993254	35072250	473975188	47470707	267251171
2026	1303750432	35446201	424754060	48215354	205260889
2027	1290507610	35820151	375158981	48960001	142525961
2028	1277264788	36194101	325189952	49704647	79046385
2029	1264021966	36568051	274846972	50449294	14822164
2030	1250779144	36942002	224130043	51193941	-50146705
2031	1237536322	37315952	173039163	51938587	-115860220
2032	1224293500	37689902	121574333	52683234	-182318382
2033	1211050678	38063852	69735552	53427880	-249521190
2034	1197807856	38437803	17522821	54172527	-317468645
2035	1184565034	38811753	-35063860	54917174	-386160747
2036	1171322212	39185703	-88024491	55661820	-455597495
2037	1158079390	39559653	-141359072	56406467	-525778890
2038	1144836568	39933604	-195067604	57151113	-596704931
2039	1131593746	40307554	-249150086	57895760	-668375619

GLOSSARY

Aggregate Any of several hard, inert materials, such as sand, gravel, crushed stone or combinations thereof, used for mixing in various-sized fragments with a cementing or bituminous material to form concrete, mortar, asphalt or plaster; or used alone as in railroad ballast or graded fill. Fine aggregate is the material that will pass a 0.25-inch screen, and coarse aggregate is the material that will not pass a 0.25-inch screen.

Basalt A fine-grained, dark-colored volcanic rock. Composed mostly of ferromagnesian minerals (silicates that contain iron and magnesium) and feldspar.

Bedrock aggregate Crushed rock (hard, solid bedrock) used as aggregate.

Biochemical sedimentary rock Sedimentary rock composed dominantly of the skeletal parts of shelly organisms, such as some limestones.

Boulder A rock fragment larger than 256 mm (10 inches) in diameter.

Carbonate rock A rock comprising more than 50 percent (by weight) calcite or dolomite or mixtures of the two, such as limestone or dolostone (dolomitic rock).

Chemical sedimentary rock Sedimentary rock composed of chemical precipitates from supersaturated natural solutions; includes rock salt and gypsum.

Clastic sedimentary rock Sedimentary rock composed of fragments of older rocks that have been transported from their source, and deposited by water, wind, or ice.

Cobble A rock fragment between 64 mm (2.5 inches) and 256 mm (10 inches) in diameter.

Dolostone A carbonate sedimentary rock that contains more than 90 percent of the mineral dolomite and less than 10 percent of the mineral calcite. Dolostone is commonly referred to as dolomite, dolomite rock, or dolomitic rock.

Drift An informal term applied to all sediments (clay, sand, gravel, boulders) transported by a glacier and deposited directly by the ice, or by running water emanating from the ice. This term is not currently used in the technical literature; it includes till and outwash deposits.

Esker A long, low, narrow, sinuous, steep-sided ridge or mound composed of irregularly stratified sand and gravel that was deposited by a subglacial or englacial stream flowing between ice walls or in an ice tunnel of a continuously retreating glacier, and was left behind when the ice melted. It may be branching and is often discontinuous.

Fault A surface or zone of rock fracture along which there has been displacement.

Felsite An igneous rock in which either the whole or the greater part consists of very fine crystals of the minerals feldspar and quartz. Most felsites are light gray, buff, or pink in color.

Fold A curve or bend of rock layers.

Granite An igneous rock which formed beneath the surface of the earth by the cooling and crystallization of magma. Contains quartz, and is composed mostly of potassium- and sodium-rich feldspar minerals.

Gravel General term for sediment composed of pebbles, cobbles, and boulders. Commercially, the term gravel indicates a sedimentary deposit composed of 20 percent or more pebbles, cobbles and boulders, admixed and interstratified with sand.

Graywacke A type of sandstone that contains more than 15 percent matrix material (clay, other fine-grained minerals) among sand-sized detrital grains of quartz and feldspar. Typically a greenish gray-brown color, and hard.

Ice-contact deposit Stratified glacial sediment deposited in contact with glacier ice.

Igneous rock Rock which has solidified from molten or partly molten rock.

Iron oxide An engineering term applied to rocks that are impregnated, coated or composed of iron oxides in various forms. Such materials are undesirable constituents in construction aggregate.

Kame A long, low, steep-sided hill, mound, knob, hummock or short, irregular ridge, composed chiefly of stratified sand and gravel deposited by a subglacial stream as an alluvial fan or delta against or upon the terminal margin of a melting glacier, and generally aligned parallel to the ice front.

Limestone. A carbonate sedimentary rock containing more than 95 percent of the mineral calcite and less than 5 percent of the mineral dolomite. Carbonate rocks containing between 5 and 50 percent dolomite and 50 to 95 percent calcite are referred to as dolomitic limestones.

Metamorphic rock Rock which has formed in the solid state in response to pronounced changes of temperature, pressure, and chemical environment, which take place, in general, below the surface zones of weathering and cementation.

Moraine A mound, ridge or other distinct accumulation of unsorted, unstratified glacial sediment, predominantly till, deposited chiefly by direct action of glacier ice in a variety of depositional environments. Prominent moraines typically form at the margins of stagnating glaciers or ice sheets, where complex processes associated with ice flow and melting produce distinctive deposits and an intricate landscape of irregular hills and closed depressions.

Outwash Sand and gravel transported or “washed out” from a glacier by meltwater streams and deposited in front of or beyond the terminal moraine or the margin of an active glacier or ice sheet.

Pebble A rock fragment between 2 mm (0.8 inches) and 64 mm (2.5 inches) in diameter.

Pit (commercial sense) An opening in the land surface from which unconsolidated rock materials are excavated for sale or commercial use.

Quarry A mine or opening in the land surface from which consolidated rock materials are excavated for sale or commercial use.

Rip-Rap Large blocks of rock used to stabilize or armour erodable streambanks and slopes.

Sand Grains of rocks or minerals that range from .062 mm (.002 inches) to 2 mm (.08 inches) in diameter. Sand grains are divided into five categories, depending on grain size. These are: very coarse 1–2 mm; coarse 0.5–1 mm; medium 0.25–0 5 mm; fine 0.25–0.125 mm; very fine 0.125–0.062 mm.

Sedimentary rock A rock resulting from the consolidation of loose sediment that has accumulated in layers (see also Clastic sedimentary rock, Chemical sedimentary rock, and Biochemical sedimentary rock).

Shale A sedimentary rock consisting of thinly laminated and compressed clay. It has a low specific gravity and high absorption. Shale is a spall material (see below), that is highly deleterious to concrete.

Short ton Two thousand pounds. The term ton is used for short ton in this report.

Sorting A term used to indicate the amount of uniformity in particle size of a sediment; a well-sorted sediment contains particles of similar size.

Spall materials A term used by construction engineers to denote rock types that have detrimental qualities of such magnitude that they will undoubtedly cause a pop-out or spall in hardened concrete.

Standard sieves The fundamental data for standard sieves (0.25 inch and No. 4) mentioned in this report are as follows:

Sieve Designation	Sieve openings millimeters	inches	Wire diameter millimeters	inches
coarse series 1/4 inch (No. 3)	6.35	0.250	1.6–2.11	0.63–0.83
fine series 4760 micron (No. 4)	4.76	0.187	1.14–1.68	0.45–0.66

Supraglacial Above (on top of) a glacier.

Terrace Any long, narrow, relatively level or gently inclined surface, generally less broad than a plain, bounded along one edge by a steeper descending slope, and along the other by a steeper ascending slope; a large bench or step-like ledge breaking the continuity of a slope.

Till Unsorted and unstratified glacial sediment, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by water from the glacier, and consisting of a heterogeneous mixture of clay, sand, gravel and boulders.

Unsound chert A sedimentary rock composed mainly of very fine-grained silica, and which typically has a dull white chalk-like appearance and is quite absorptive. It is considered deleterious in aggregate deposits.

Valley fill Unconsolidated sediment that fills or partially fills a valley. The sediment may be deposited by flowing water, wind, or glacial processes.

Valley train A long, narrow body of outwash, deposited by meltwater streams far beyond the terminal moraine or the margin of an active glacier and confined within the walls of a valley below the glacier. It may or may not emerge from the mouth of the valley to join an outwash plain.

BIBLIOGRAPHY

The Bibliography is divided into two sections. In the General section all the references cited in Parts I, II, and III of this report are listed, as well as references that give the reader additional information that relates to the main body of the report. In the County Geology section, references that provide geologic information relating to the descriptions of the natural aggregate and bedrock aggregate deposits are listed on a county-by-county basis.

GENERAL

Eng, M.T., and Costello, M.J., 1979, Industrial minerals in Minnesota—a status report on sand, gravel, and crushed rock: Minnesota Department of Natural Resources, Division of Minerals, 76 p.

Gary, M., McAfee, R.J., and Wolf, C.L., eds., 1974, Glossary of geology: American Geological Institute, 805 p.

Goebel, J.E., 1976, Quaternary geologic map index of Minnesota: Minnesota Geological Survey Report of Investigations 15, 1 pl. in pocket, 22 p.

Hoagberg, R.K., and Rajaram, V., 1980, Minnesota aggregate resources study for Local Road Research Board Investigation No. 652: Ernest K. Lehmann & Associates, Volume I: Executive Summary, 9 p., Volume II: Report, 179 p.

Hobbs, H.C., 1999, Surficial geology of the Hastings 30 x 60 quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-96, scale 1:100,000.

Hobbs, H.C., and Goebel, J.E., 1982, Geologic map of Minnesota, Quaternary geology: Minnesota Geological Survey State Map Series S-1, scale 1:500,000.

Hogberg, R.K., 1970, Geologic map of the Minneapolis quadrangle, Minnesota (Surficial geology): Unpublished map, Minnesota Geological Survey.

Jirsa, M.A., Olsen, B.M., and Bloomgren, B.A., 1986, Bedrock geologic and topographic maps of the seven-county Twin Cities Metropolitan Area, Minnesota: Minnesota Geological Survey Miscellaneous Map M-55, scale 1:125,000.

Lawrence Group, 1999, TLG Street Centerline and Address Ranges, electronic data, HYPERLINK http://www.datafinder.org/metadata/tlg0003.htm#metainfo

Lusardi, B.A., 1997, Surficial geologic map of the Shakopee quadrangle, Carver, Scott, and Hennepin Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-87, scale 1:24,000.

Lusardi, B.A., 1998, Surficial geologic map of the Jordan East quadrangle, Carver and Scott Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-89, scale 1:24,000.

Lusardi, B.A., 1999, Surficial geologic map of the Mound quadrangle, Carver and Hennepin Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-93, scale 1:24,000.

Marshall, L.G., 1963, Sand and gravel operations and costs, Minneapolis-St. Paul area, Minnesota: U.S. Bureau of Mines Information Circular 8157, 66 p.

Metropolitan Council, 1993, An overview of historical population and housing trends in the Twin Cities metropolitan area: Metropolitan Council Publication No. 620-93-034, 41 p.

Metropolitan Council, 1995, 1990 Land use profiles and acreage summaries and maps by community: Metropolitan Council Publication No. 74-95-061, x p.

Metropolitan Council, 1996, Final Household and Population Forecasts, 2000-2050: Unpublished Metropolitan Council data, 2 p.

Metropolitan Council, 1996, Regional Blueprint, Twin Cities Metropolitan Area: Metropolitan Council Publication No. 78-97-007, 84 p.

Metropolitan Council, 1997, Adjusted Household Estimates, 1980-1996: Unpublished Metropolitan Council data, 12 p.

Metropolitan Council, 1997, Adjusted Population Estimates, 1980-1996: Unpublished Metropolitan Council data, 12 p.

Metropolitan Council, 1997, 1997 Digital orthophotography seven-county metropolitan area of Minneapolis-St. Paul, Minnesota: Metropolitan Council, set of 77 CDs.

Metropolitan Council, 1998, Interim forecasts of population, households and employment, Twin Cities metropolitan area, April 1998 (revised): Unpublished Metropolitan Council data, 6 p.

Metropolitan Council, 1998, 1997 Employment by City/Township Twin Cities metropolitan area: Metropolitan Council Publication No. 74-98-031 7 p.

Metropolitan Council, 1999, Major new residential construction projects in the Twin Cities metropolitan area: Metropolitan Council Publication No. 74-99-030, 82 p.

Metropolitan Council, 1999, Metropolitan agricultural preserves status report: Metropolitan Council Publication No. 78-99-004, 9 p.

Metropolitan Council, 1999, Population and household estimates, April 1, 1998 for the Twin Cities metropolitan area: Metropolitan Council Publication No. 74-99-028, 5 p.

Metropolitan Council, 1996, Community Development Division, GIS Section, Growth Management Policy Areas, (unpublished) HYPERLINK http://lucy.lmic.state.mn.us/metadata/gmpa.html

Metropolitan Council, 1999, Community Development Division, GIS Section, 1997 Generalized Land Use: Unpublished metropolitan Council electronic data.

Minnesota Department of Revenue, 2000, Mineral tax information for 1990-98 for the Twin Cities Metropolitan Counties: Minerals Tax Office, Eveleth, Minnesota, unpublished electronic data.

Minnesota Department of Revenue, 1997, Aggregate tax collected by county—1996: Minerals Tax Office, Mining Tax Guide, Fig. 36, p. 45.

Minnesota Department of Revenue, 1998, Aggregate tax collected by county—1997: Minerals Tax Office, Mining Tax Guide, Fig. 38, p. 45.

Meyer, G.N. 1985, Quaternary geologic map of the Minneapolis-St. Paul urban area, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-54, scale 1:48,000.

Meyer, G.N., 1999, Surficial geology of the Stillwater 30 x 60 minute quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-95, scale 1:100,000.

Meyer, G.N., and Jirsa, M.A., 1984, Aggregate resources inventory, Twin Cities metropolitan area, Minnesota: Minnesota Geological Survey Information Circular 20, 16 p., 2 maps, scale 1:250,000.

Meyer, G.N., and Mossler, J.H., 1999, Primary sources of construction aggregate in the seven-county metropolitan area, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-102, two plates, scale 1:100,000.

Meyer, G.N., and Patterson, C.J., 1999, Surficial geology of the Anoka quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-97, scale 1:100,000.

Minnesota Statutes, section 298.75.

Minnesota Statutes, sections 473.851 to 473.866.

Mossler, J.H., 1983, Bedrock topography and isopachs of Cretaceous and Quaternary strata, east-central and southeastern Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-52, scale 1:500,000.

Nelson, S. L., Oberhelman, M. W., Olson, D. J., 1990, Inventory of industrial pits and quarries in Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 282, 415 p., 2 volumes.

Niles, H. B., and Mossler, J. H., 1990, Evaluation of the carbonate resources of southern Minnesota: University of Minnesota, Natural Resources Research Institute Technical Report NRRI/TR90/08, 200p.

Norvitch, R.F., and Walton, M.S., eds., 1979, Geologic and hydrologic aspects of tunneling in the Twin Cities area, Minnesota: U.S. Geological Survey Miscellaneous Investigations Series Map I-1157, 7 plates.

Resources and Reserves Committee, 1999, A guide for reporting exploration information, mineral resources, and mineral reserves: Littleton, Colo., unpubl. report submitted to the Board of Directors, Society for Mining, Metallurgy and Exploration, 17 p.

Sardeson, F.W., 1916, Minneapolis-St. Paul folio, Minnesota: U.S. Geological Survey Geologic Atlas, Folio 201, 14 p.

Schenk, C., and Jouseau, M., 1983, Aggregate resources in the Twin Cities metropolitan area: Metropolitan Council of the Twin Cities Area Publication No. 10-83-019, 100 p.

Schenck, G.H.K., and Torries, T.F., 1975, Crushed stone, *in* Industrial minerals and rocks, 4th edition, S.J. Lefond, editor, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 66–84.

Schwochow, S.D., 1974, Mineral resources included in H.B. 1041, *in* Guidelines and criteria for identification and land-use controls of geologic hazard and mineral resource areas: Colorado Geological Survey Special Publication 6, p. 77–105.

Twin Cities Metropolitan Planning Commission, The Joint Program, Metropolitan Population Study, Planning Report (undated).

U.S. Bureau of the Census, 1952, U.S. Census of Population—1950, Vol. 1, Number of Inhabitants: U.S. Government Printing Office, Washington, D.C.

U.S. Bureau of the Census, 1961, U.S. Census of Population—1960, Vol. 1, Characteristics of the Population, Part A, Number of Inhabitants: U.S. Government Printing Office, Washington, D.C.

U.S. Bureau of the Census, 1973, U.S. Census of Population—1970, Vol. 1, Characteristics of the Population, Part 25, Minnesota: U.S. Government Printing Office, Washington, D.C.

U.S. Geological Survey, 1999, Mineral Industry Surveys, Minnesota, 1998 annual estimate: The Survey, 8 p.

Wahl, T.E., and Tipping, R.G., 1991, Ground-water Data Management—The County Well Index: Minnesota Geological Survey, variously paged in 3-ring binder.

Washington County Planning, 1999, Draft Environmental Impact Statement—Lakeland Sand and Gravel Mine Expansion and Reclamation Plans, Lakeland and West Lakeland Township, Minnesota: Draft Environmental Impact Statement, CAMAS Minnesota Inc.

Wright, H.E., Jr., 1972, Quaternary history of Minnesota *in* Sims, P.K., and Morey, G.B., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 515–547.

COUNTY GEOLOGY

Anoka County

Chamberlain, L.M. 1977, Soil survey of Anoka County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 92 p.

Cooper, W.S., 1935, The history of the upper Mississippi River in Late Wisconsin and post glacial time: Minnesota Geological Survey Bulletin 26, 116 p.

Farnham, R.S., 1956, Geology of the Anoka sand plain: in Glacial geology, eastern Minnesota, Geological Society of America Guidebook Series, G.M. Schwartz, editor, Field Trip No. 3, p. 53-64.

Farnham, R.S., et al., 1958, Soil survey of Isanti County, Minnesota: U.S Department of Agriculture, Soil Conservation Service, 60 p.

Grimes, M.F., 1968, Soil survey of Sherburne County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 81 p.

Lehr, J.D., 1992, Aggregate resources and Quaternary geology of Isanti County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 304, pl. I, scale 1:100,000.

Meyer, G.N., 1993, Quaternary geologic map of Sherburne County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-77, scale 1:100,000.

Meyer, G.N., Patterson, C.J., Hobbs, H.C., and Lehr, J.D., 1993, Surficial geology, pl. 1 in Meyer, G.N., and Falteisek, J., eds., Regional hydrogeologic assessment, Anoka Sand Plain-Anoka, Chisago, Isanti and Sherburne Counties, Minnesota: Minnesota Department of Natural Resources, Division of Waters Regional Assessment Series RHA-1, scale 1:200,000.

Smith, W.G., Nelson, G.H., and Roth, E.G., 1918, Soil survey of Anoka County, Minnesota: U.S. Department of Agriculture, Bureau of Soils, Advance Sheets, Field operations of Bureau of Soils, 1916, 30 p.

Carver County

Edwards, R.J., 1968, Soil survey of Carver County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 88 p.

Lusardi, B.A., 1998, Surficial geologic map of the Victoria quadrangle, Carver County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-88, scale 1:24,000.

Dakota County

Arneman, H.F., 1960, Soil survey of Dakota County, Minnesota: U.S. Department of Agriculture, Soil Conservation Services 52 p.

Balaban, N.H., and Hobbs, H.C., eds., 1990, Geologic atlas of Dakota County, Minnesota: Minnesota Geological Survey County Atlas Series C-6, scale 1:100,000, 9 plates.

Gelineau, W.J., 1959, Pleistocene geology of the Inver Grove and St. Paul SW quadrangles, Minnesota: Unpublished M.S. thesis, University of Minnesota, 77 p.

Hundley, S.J, 1983, Soil survey of Dakota County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 272 p.

Matsch, C.L., 1962, Pleistocene geology of the St. Paul Park and Prescott quadrangles: Unpublished M.S. thesis, University of Minnesota, 49 p.

Poch, G.A., 1976, Soil survey of Goodhue County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 129 p.

Savina, M., Jacobson, R., and Rodgers, D., 1979, Outwash deposits of central Dakota County, Minnesota: Minnesota Geological Survey file report, 81 p.

Hennepin County

Balaban, N.H., ed., 1989, Geologic atlas of Hennepin County, Minnesota: Minnesota Geological Survey County Atlas Series C-4, scale 1:100,000, 9 plates.

Edwards, R.J., 1968, Soil survey of Wright County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 140 p.

Lehr, J.D., 1991, Aggregate resources and Quaternary geology of Wright County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 294, 23 p., 1 plate, scale 1:100,000.

Lueth, R.A., 1974, Soil survey of Hennepin County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 159 p.

McMiller, P.R., et al., 1929, Soil survey of Hennepin County, Minnesota: U.S. Department of Agriculture, Bureau of Chemistry and Soils, 34 p.

Ramsey County

Eginton, C.W., 1975, Geology of the White Bear Lake West quadrangle, Minnesota: Unpublished M.S. thesis, Oklahoma State University, Stillwater, 56 p.

Meyer, G.N., and Swanson, L., eds., 1992, Geologic atlas of Ramsey County, Minnesota: Minnesota Geological Survey County Atlas Series C-7, scale 1:48,000, 10 plates.

Smith, W.G., and Kirk, N.M., 1916, Soil survey of Ramsey County, Minnesota: U.S. Department of Agriculture, Bureau of Soils, Advance Sheets, Field operations of Bureau of Soils, 1914, 37 p.

Stone, J.E., 1966, Surficial geology of the New Brighton quadrangle, Minnesota: Minnesota Geological Survey, Geologic Map Series GM-2, 34 p.

Vinar, K.R., 1980, Soil survey of Washington and Ramsey Counties, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 246 p.

Scott County

Balaban, N.H., and McSwiggen, P.L., eds., 1982, Geologic atlas of Scott County, Minnesota: Minnesota Geological Survey County Atlas Series C-1, scale 1:100,000, 6 plates.

Carlson, C.R., et al., 1975, Soil survey of Rice County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 118 p.

Harms, G.F., 1959, Soil survey of Scott County, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 93 p.

Lusardi, B.A., 1999, Surficial geologic map of the Jordan West quadrangle, Scott County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-94, scale 1:24,000.

Washington County

Ellingson, J.B., 1998, Aggregate resource evaluation: Sand and gravel evaluation for a site near Bayport, Washington County, Minnesota: Minnesota Department of Natural Resources Minerals Division - Minerals Potential Project and Report #334-1, 25 p.

Matsch, C.L., 1962, Pleistocene geology of the St. Paul Park and Prescott quadrangles: Unpublished M.S. thesis, University of Minnesota, 49 p.

Meyer, G.N., 1993, Quaternary geologic map of Chisago County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-78, scale 1:100,000.

Swanson, L., and Meyer, G.N., eds.,1990, Geologic atlas of Washington County, Minnesota: Minnesota Geological Survey County Atlas Series C-5, scale 1:100,000, 7 plates.

Vinar, K.R., 1980, Soil survey of Washington and Ramsey Counties, Minnesota: U.S. Department of Agriculture, Soil Conservation Service, 246 p.