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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

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MINNESOTA GEOLOGICAL SURVEY
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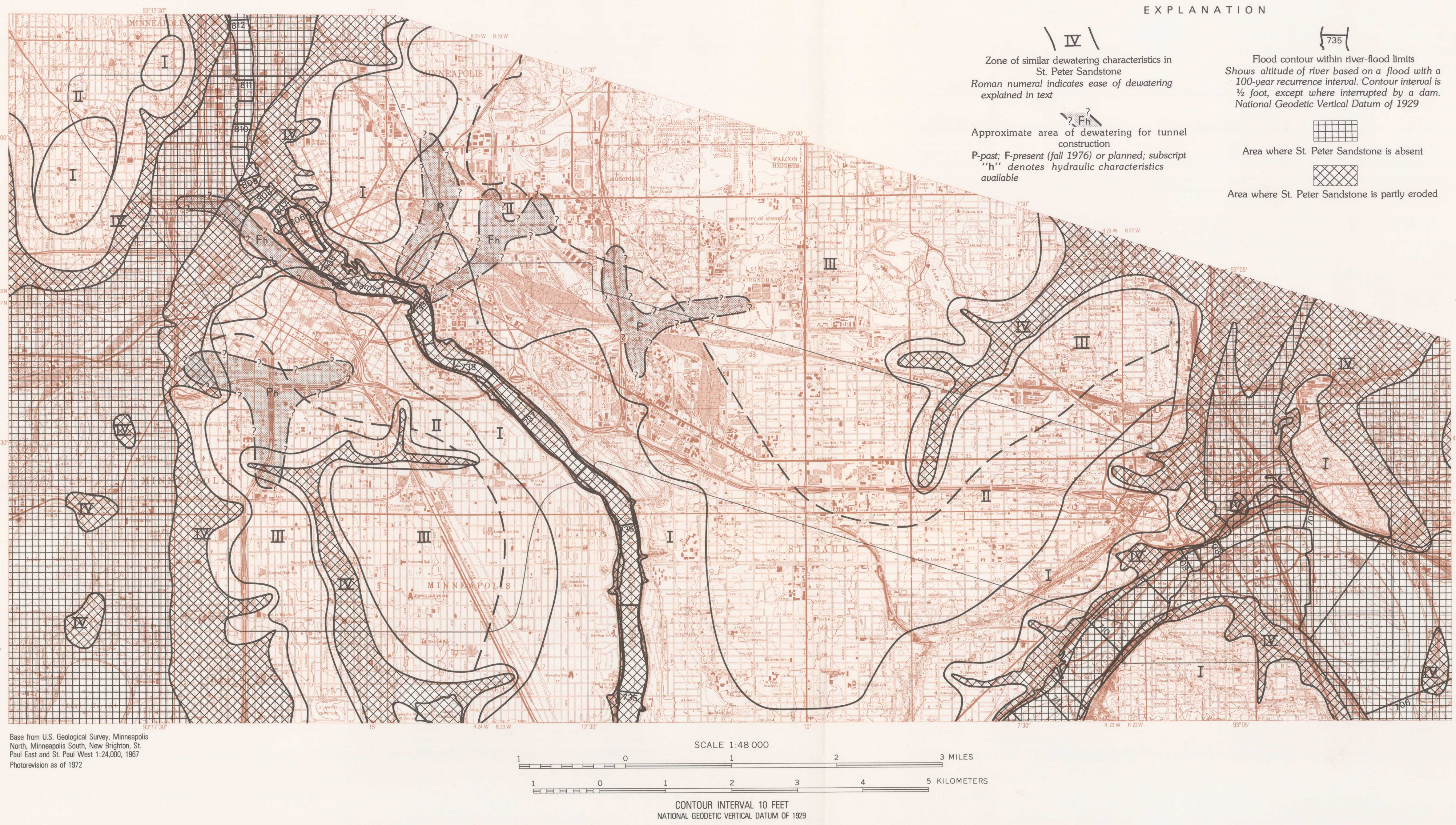
MISCELLANEOUS INVESTIGATIONS SERIES
MAP I–1157
PLATE 7


EXPLANATION

IV — Zone of similar dewatering characteristics in St. Peter Sandstone
Roman numeral indicates ease of dewatering explained in text

735 — Flood contour within river-flood limits
Shows altitude of river based on a flood with a 100-year recurrence interval. Contour interval is ½ foot, except where interrupted by a dam. National Geodetic Vertical Datum of 1929

Fh — Approximate area of dewatering for tunnel construction
P-past; F-present (fall 1976) or planned; subscript "h" denotes hydraulic characteristics available

▦ Area where St. Peter Sandstone is absent

▨ Area where St. Peter Sandstone is partly eroded

Base from U.S. Geological Survey, Minneapolis North, Minneapolis South, New Brighton, St. Paul East and St. Paul West 1:24,000, 1967
Photorevision as of 1972

SCALE 1:48 000
CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 7.—ZONES OF SIMILAR DEWATERING CHARACTERISTICS IN ST. PETER SANDSTONE, SELECTED PLACES OF ACTUAL TUNNEL DEWATERING, AND FLOOD LIMITS ALONG THE MISSISSIPPI RIVER

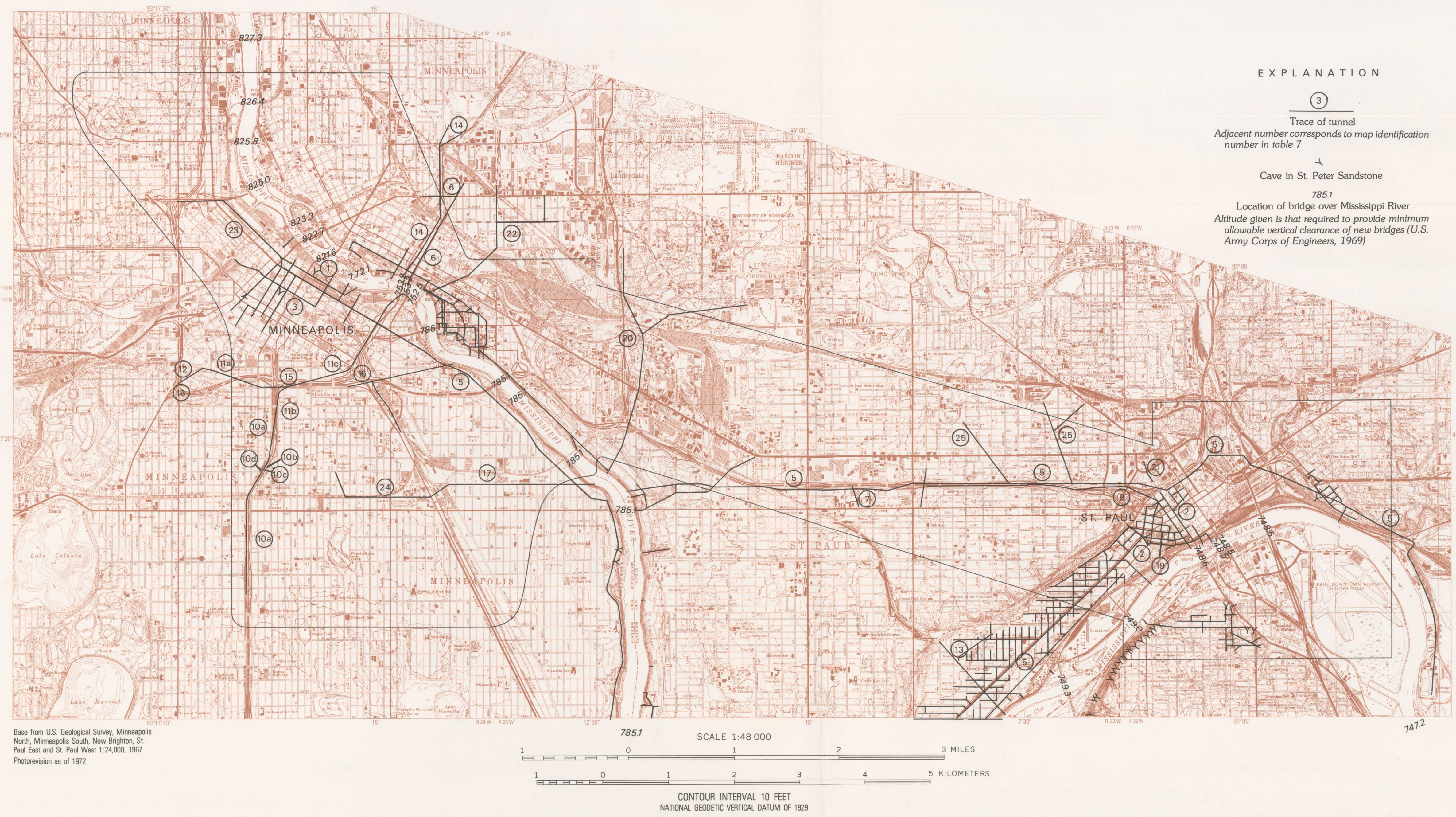
Generalized zones with similar dewatering characteristics in the St. Peter Sandstone are shown in figure 7. The zonal boundaries are based on positions of water levels and locations of lateral hydrologic boundaries in the sandstone. Dewatering becomes progressively more difficult from zone I to zone III. Tunnel-dewatering costs could be lessened by staying in the lower-numbered zones.

In zone I, tunnels through the upper 20 feet of sandstone would require little dewatering, if overlying confining strata were not ruptured. Similar tunnels in zone II would require more dewatering as the boundary of zone III was approached, because water-level altitudes are higher in zone III and pumpage cones would induce flow from fully saturated parts of the sandstone into the pumping (or drain) centers. Dewatering needs will be maximal in parts of zone III where the sandstone is fully saturated and mostly confined conditions prevail; that is, where water levels in wells finished in the sandstone rise above the base of the overlying confining bed. (See figure 5.)

The relative ease of dewatering in zone IV is uncertain. In places the sandstone is dry and tunnels in its upper part would require little, if any, dewatering. But, any dewatering done in tunnels dug at or below the elevation of the Mississippi River could intercept the river system as a positive recharge boundary, thus intensifying pumping needs. Similarly, buried drift-filled valleys can be intercepted laterally by pumping cones of depression. In these valleys, the hydrologic boundary could be either positive or negative, however, depending on the composition of the valley fill. If the fill is mostly saturated sand and gravel, it could act as a positive boundary and add to pumping needs. If mostly clay, it could act as a negative boundary and reduce pumping needs.

Several areas where dewatering in St. Peter Sandstone has been or will be done are included on figure 7. The boundaries of the areas are approximations because it is not known how far laterally (or vertically) the effects of dewatering were (or will be) felt. In the most centrally located dewatered area (just southwest of the State Fairgrounds), the sandstone was dewatered along a sewer tunnel that ranged from 140 to 170 feet below land surface and within 30 feet of the top of the sandstone. The wells were finished about 60 feet below the bottom of the tunnel and were spaced from 600 to 1,200 feet apart. The pumping rates of each well were estimated at 450 to 600 gallons per minute. Costs for dewatering vary and commonly are estimated at $30 per linear foot (1976), but a cost of $100 per foot has been reported for one tunnel.

The limits and water-surface altitudes of the 100-year probability flood are also shown on figure 7. The difference between flood levels and normal river levels in the study area range from 6 feet in the pool behind St. Anthony Falls dam to 11.5 feet near river mile 842, where the Mississippi River crosses the southern boundary of the study area.


EXPLANATION

③ Trace of tunnel
Adjacent number corresponds to map identification number in table 7

Cave in St. Peter Sandstone

785.1 Location of bridge over Mississippi River
Altitude given is that required to provide minimum allowable vertical clearance of new bridges (U.S. Army Corps of Engineers, 1969)

Base from U.S. Geological Survey, Minneapolis North, Minneapolis South, New Brighton, St. Paul East and St. Paul West 1:24,000, 1967
Photorevision as of 1972

SCALE 1:48 000
CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 8.—SELECTED TUNNEL LOCATIONS, CAVES IN ST. PETER SANDSTONE, AND ALLOWABLE VERTICAL CLEARANCE OF BRIDGES CROSSING THE MISSISSIPPI RIVER

Existing drain tunnels are major manmade constraints to new tunneling in the St. Peter Sandstone. Tunnel-plan data, especially profile data, are too voluminous to compile for this particular report. These data can best be obtained when specific routes are proposed. Traces of the major tunnels in the sandstone are shown in figure 8. Map identification numbers placed near the traces refer to the tunnel information listed in table 7. Detailed plans of most existing tunnels are available in the public works departments of the respective cities. St. Paul maintains a composite record of tunnel locations on a city street map (City of St. Paul, 1972). The location of tunnels in Minneapolis must be compiled from individual project plans. Similarly, drain-tunnel locations for State highways must be compiled from individual plans kept by the Minnesota Department of Transportation.

Caves in the St. Peter Sandstone are also shown on figure 8. St. Paul Department of Public Works has a record of locations of caves within the city (City of St. Paul, 1972).

Other constraints that could be important to tunnel construction are minimum-vertical-clearance restrictions for bridges crossing commercially navigable parts of the Mississippi River. These restrictions would apply where tunnel segments on opposite banks of the river must be connected by bridges. The criterion for minimum clearance across the river upstream to river mile 853.0 (near the northwest corner of the University of Minnesota campus) is 60 feet above project (or flat) pool or 53 feet above the 2 percent flow line, whichever is greater (U.S. Army Corps of Engineers, 1969). Between river miles 853.0 and 857.6, in Minneapolis Upper Harbor, the minimum clearance is 21.4 feet above river stage at a flow of 40,000 cubic feet per second. The restrictive altitudes, shown at sites of present bridges spanning the river, are plotted on figure 8. Regulatory control for this constraint is the responsibility of the U.S. Coast Guard, whose regional office is at St. Louis, Missouri.

TABLE 6.—*Hydraulic characteristics of some bedrock units, as determined from field pumping tests and laboratory analyses*

Rock Unit	Porosity Percent[1]	Hydraulic Conductivity, ft/day[1] Horizontal, K	Vertical, K′	Transmissivity, T, gpd/ft ~~ft²/day~~	Storage Coefficient, S	Location		Remarks	Source of Information
Platteville Formation				40,000	. .	NE¼SE¼SW¼NE¼	Sec. 18, T. 28 N., R. 23 W.	Short distance south of map area	Liesch, 1973
				36,000	2.6x10−3	Do.	Do.	Do.	Do.
				1400	. .	Do.	Do.	Do.	Do.
				3840	4.0x10−5	SE¼NE¼SW¼NE¼	Do.	Do.	Do.
				5000	1.2x10−4	Do.	Do.	Do.	Do.
				5200	4.2x10−5	NW¼NE¼SW¼NE¼	Do.	Do.	Do.
				4200	4.0x10−3	Do.	Do.	Do.	Do.
				4000	4.0x10−3	NE¼NW¼SW¼NE¼	Do.	Do.	Do.
				7000	1.8x10−5	Do.	Do.	Do.	Do.
				5700	. .	SE¼SW¼NW¼NE¼	Do.	Do.	Do.
				2900	. .	NW¼SW¼NW¼NE¼	Do.	Do.	Do.
St. Peter Sandstone				20,800	3.3x10−4	NE¼SE¼SE¼	Sec. 27, T. 29 N., R. 24 W.		Liesch, 1962
				22,400	. .	SW¼NE¼SW¼	Do.		Do.
				20,800	9.75x10−3	SW¼NW¼SE¼	Sec. 26, T. 29 N., R. 24 W.		Do.
				18,000	9.0x10−5	SE¼SW¼SE¼	Sec. 8, T. 117 N., R. 21 W.	Outside of map area	Barr Eng., 1976
	28.3	Range 0.16–26.9 Median 12.5	Range 0.03–43.9 Median 10.9					10 samples to determine porosity and K; 5 samples to determine K′	Norvitch and others, 1973
	28.4	2.84	3.12			NW¼NE¼	Sec. 17, T. 28 N., R. 23 W.	Alt. 717, Ford Mine; short distance south of study area	U.S.C.E., 1939
	29.3	9.64	. .			Do.	Do.	Alt. 714, Ford Mine; no fractures	Do.
	. .	13.33	. .			Do.	Do.	Alt. 714, Ford Mine; minor fractures	Do.
	. .	16.73	. .			Do.	Do.	Alt. 714, Ford Mine; badly fractured	Do.
	29.6	10.21	11.45			Do.	Do.	Alt. 710, Ford Mine; no fractures	Do.
	28.3	10.49	. .			Do.	Do.	Alt. 712, Ford Mine; test blocks fractured	Do.
Prairie Du Chien Group				51,500[2]	5.0x10−5	SE¼SE¼SW¼	Sec. 19, T. 28 N., R. 22 W.	Outside of map area	Norvitch and others, 1973
				46,800[2]	1.1x10−5	SW¼SW¼SE¼	Do.	Do.	Do.
				55,000	3.4x10−4	SW¼NW¼SW¼	Sec. 29, T. 118 N., R. 22 W.	Do.	Do.

[1] Determined from laboratory analyses.
[2] Average of test results.

Hydraulic characteristics of aquifers must be determined in order to plan for dewatering of tunnels. If values of transmissivity (T) and storage coefficient (S), are known, well spacing and pumping rates can be estimated through use of known formulas (Ferris and others, 1962; Hantush and Jacob, 1955). Though the T and S values cited in table 6 are too sparse to provide values for each aquifer, they suggest magnitudes for aquifers in the Twin Cities areas. Pumping-test data are lacking for aquifers in the surficial deposits.

The horizontal and vertical hydraulic conductivities (K and K′ respectively), and porosity values in table 6 were determined by laboratory analysis. Estimates of T can be derived through use of the formula $T=Km$, where m is thickness of the aquifer, in feet. The St. Peter Sandstone aquifer ranges in thickness from a feather edge to 150 feet in the study area. (See Norvitch and others, 1973, fig. 11.)

Though storage coefficients included in the table indicate that confined artesian conditions prevail, figure 5, plate 6 shows that water in the St. Peter aquifer is unconfined locally where the hydrostatic head is below the top of the sandstone. Here storage coefficients probably range from about 0.05 to 0.15.

A hydraulic parameter dependent on T and S values is hydraulic diffusivity, T/S. This parameter governs the rate at which the effects of pumping will spread through an aquifer. In artesian aquifers hydraulic diffusivity is commonly large, and drawdown effects from a well spread rapidly. In water-table aquifers diffusivity is commonly much smaller, so drawdown spreads at a much slower rate. This parameter is significant when considering the effects of dewatering on nearby wells completed in the same aquifer. Pumpage from wells in aquifers having high T values creates less drawdown than pumpage from wells in aquifers having low T values.

Hydraulic properties of the Platteville aquifer are nonuniform as shown by the wide range in T values shown in table 6. Thus, it is difficult to predict with any degree of confidence the effects of pumping in this aquifer. Hydraulic properties of the St. Peter aquifer, at least in its upper part, are more nearly uniform and the effects of pumping are more readily predictable.

Values of T in the drift deposits are extremely variable, from very low in clayey till to high in sand and gravel. Hydraulic characteristics for the till would be applicable to specific sites only.

TABLE 7.—*Data on tunnels in the Twin Cities area*

Map[1] Identification Number	Year(s) of Construction	Tunnel name or location	Geologic Material Penetrated	Purpose	Finished tunnel inside cross section[2] Dimensions or Diameter (in feet)	Area (in square feet)	Length (in feet; miles where designated)	Cost[2] per linear foot of completed tunnel	Cost[2] per cubic foot of completed tunnel	Remarks
1	1869	Minneapolis, under St. Anthony Falls	St. Peter Sandstone		. .	. .	1,500E[3]	. .	. .	Tunnel collapsed when partly finished, abandoned when too much water entered
2	1870–1940	Downtown St. Paul and SW of downtown	Do.	Utility	Variable	. .	10,000E	. .	. .	All tunnels dry
3	1835	Minneapolis, North	Do.	Sewer	7.5x7.9	59E	5,000E	. .	. .	Hand picks and blasting
4	1922	Minnehaha Tunnel (south of study area)	Do.	Do.	. .	. .	3,000E	. .	. .	Do.
5	1935–1938	Minneapolis to St. Paul	Surficial deposits	Do.	9.6x10 or 13.3	96 or 149E	9,200	. .	. .	Open cut method
		Do.	St. Peter Sandstone[4]	Do.	11.8, 13.3 or 13.8	107, 150, 150E	39,570[4]	. .	. .	Air chisels; no outside dewatering, inflow of water as much as 3,200 gallons per minute
		Minneapolis	Do.	Do.	3.5x6 to 9.5	21 to 71E				
		Minneapolis	Surficial deposits	Do.	. .	. .	14 miles	. .	. .	Blasting, drilling; tunnel dry along river
		St. Paul	St. Peter Sandstone	Do.	5.5 or smaller	24 or less E	4 miles	. .	. .	Open cut
							75,000	30	. .	Air chisel, blasting; tunnels dry
6	1949	Minneapolis, southeast and northeast	Do.	Do.	4x6		1,700E	. .	. .	Hydraulic mining; tunnel floor at water level
		Do.	Do.	Do.	8		6,000E	18E	. .	
7	1960	St. Paul, Hamline Ave.	Decorah Shale	Do.	5.5	24E	1,297	310	12.92E	Dug by hand
8	1961	Minneapolis, Fort Snelling (south of study area)	Surficial deposits	Highway	72x17	1.224E	341	1,378E	1.13E	Cut and cover method
9	1958–1961	St. Paul, St. Peter-Rondo Streets	St. Peter Sandstone	Sewer	8	50E	3,237	169	3.37	Hydraulic mole
		Do.	Do.	Do.	9	64E	3,368	180	2.83	Do.
		Do.	Do.	Do.	12	113E	6,703	196	1.74	Hydraulic and mechanical mole
		Do.	Do.	Do.	4x6	24E	304	158	6.58	Do.
10a	1961–1963	Minneapolis, Stevens Ave.	Do.	Do.	12	113E	8,037	232	2.05	Mechanical mole
10b		Do.	Collapsed Sandstone tunnel	Do.	12	113E	187	1,520	13.44	Dug by hand, reconstruction after collapse
10c		Do.	Weathered St. Peter Sandstone adjacent to buried valley	Do.	12	113E	611	805	7.12	Hydraulic lance
10d		Do.	Clay till in buried valley	Do.	12	113E	795	920	8.13	Liner plate
11a	1963	Minneapolis, Loring Park to Central Interchange	St. Peter Sandstone	Do.	9	64E	2,821	211	3.32	Hydraulic lance; inflow of water as much as 1,800 gallons per minute
		Do.	Do.	Do.	9	64E	170	246	3.87	Hydraulic lance
11b		27th Street to Central Interchange	Do.	Do.	12	113E	5,586	261	2.30	Do.
11		Central Interchange to river	Do.	Do.	14	154E	8,194	276	1.79	Do.
12	1964	Minneapolis, Lowry Hill	Surficial deposits	Do.	10	79E	1,162	340	4.33	Liner plate
13	1964	St. Paul, Grace St.	St. Peter Sandstone	Do.	5	20E	2,394	95	4.85	Hand mined
14	1965	Minneapolis, northeast diagonal	Do.	Do.	6	28E	250	111	3.93	Hydraulic lance
		Do.	Do.	Do.	7	39E	1,059	121	3.14	Do.
		Do.	Do.	Do.	8	50E	1,246	131	2.60	Do.
		Do.	Do.	Do.	13	133E	6,791	263	1.98	Mechanical mole
		Do.	Do.	Do.	12x12	144E	261	301	2.10	Hydraulic mole
15	1966	Minneapolis, Portland Ave. and highway 94	Surficial deposits	Traffic	60x17	1,020E	390	1,590E	1.56E	Cut and cover
16	1966	Minneapolis, 16th Ave. S. and Route 55	Do.	Do.	41x16	656E	450	1,256E	1.91E	Do.
17	1967	Minneapolis, 28th St. S.	St. Peter Sandstone	Sewer	3x4	12E	585	131	10.88	Hydraulic lance
		Do.	Do.	Do.	4x6	24E	42	205	8.52	Do.
		Do.	Do.	Do.	8	50E	84	238	5.74	Do.
		Do.	Do.	Do.	8	50E	7,945	203	4.05	Do.
18	1968	Minneapolis, Lowry Hill Tunnel	Surficial deposits	Traffic	Twin 50x5.5	1,550	1,500	4,000E	2–58	Cut and cover; 17% of cost for ventilation
19	1970	St. Paul, 5th St. and St. Peter St.	St. Peter Sandstone	Sewer	6	28E	4,785	206	7.30	Hydraulic lance
		Do.	Do.	Do.	4x5.5	22	59	125	5.68E	Do.
20	1975	St. Paul, St. Anthony Area	Do.	Do.	14.6	169E	8,000E	470	2.78E	Hydraulic lance drive points unsuccessful for dewatering
		Do.	Do.	Do.	9.5	90E	4,000	. .	. .	Do.
		Do.	Do.	Do.	6	30E	600	. .	. .	Do.
21	1976	Downtown St. Paul	Do.	Telephone	5E	20E	1,200E	. .	. .	. .
22	1976–1977	Minneapolis, Como Ave. SE	Do.	Sewer	6	28E	875E	. .	. .	Under construction
		Do.	Do.	Do.	8	50E	10,525E	. .	. .	Do.
23	1977–1979	Minneapolis, 2nd St. N.	Do.	Do.	9	64E	1,000	450E	7.00E	Construction to begin within 1 year. Costs are predicted estimates and do not include $500,000 for shafts, etc.
		Do.	Do.	Do.	13	133E	5,400	670E	5.00E	Do.
		Do.	Surficial deposits	Do.	9	64E	3,050	980E	15.00E	Do.
24	1977–1980	Minneapolis, 29th St. S.	St. Peter Sandstone	Do.	. .	. .	3,600E	. .	. .	Plans not complete
25	1978	St. Paul	Do.	Do.	. .	. .	10,000E	. .	. .	Do.
26	Planned	St. Paul-Minneapolis area	Do.	Subway	Twin 14	308E	74,916E	1,477E	4.80E	Estimates from Nelson and Yardley, (1973); in 1972 dollars. Total tunneling costs.
		Do.	Do.	Do.	11x25	275E	59,168E	1.143E	4.16E	Do.
		Do.	Surficial deposits	Do.	Twin 14	368E	79,976E	3,298E	10.71E	Do.

[1] Numbers 4, 8 and 26 are not shown on Figure 8. Proposed routes for number 26 are shown in Nelson and Yardley (1973, p. 7).
[2] Information from many sources necessitated conversion to a common form. Figures may not be directly comparable as shown. Vertical shafts, dewatering, and miscellaneous costs may not be included.
[3] E-Estimated.
[4] Includes almost 800 feet of tunnel in Buried Valley drift.

TABLE 8.—*Factors related to tunnel construction*

FACTOR	GEOLOGIC UNIT[1]					SIGNIFICANCE											
	Unconsolidated deposits	Decorah Shale	Platteville Formation	Glenwood Shale	St. Peter Sandstone	Affected or induced by tunneling	No problem	Problem not severe but requires consideration	Possible severe problem locally	Possible hazard if not considered	Decreases rate of tunnel excavation	Increases rate of tunnel excavation	Affects dewatering system	Horizontal variability	Vertical variability	Increases tunneling cost	Difficulty that can be compensated for by proper techniques
All Geologic Units																	
Natural																	
Landslides	2	1	1	1	1		X										
Earthquakes	1	1	1	1	1		X										
Active faults	1	1	1	1	1		X										
Surface flooding or scouring	2	1	1	1	2			X									
Two or more ground-water systems	4	1	4	1	3			X					X	X	X		X
Complex ground-water-surface configuration	5	1	4	1	3	X				X	X		X	X	X		X
Seasonal ground-water changes expectable	5	1	5	1	5	X		X		X	X	X	X	X	X		
Long-term ground-water changes expectable	3	1	3	1	3		X										
Significant ground-water leakage to excavation	3	1	3	1	3	X			X	X	X		X	X	X	X	X
Large water inflows to tunnels	4	1	4	1	4	X			X	X	X		X	X	X	X	X
Hydrologic recharge areas	5	1	4	1	4	X		X			X		X	X	X		X
Water high in deleterious minerals	1	1	1	1	1		X										
Manmade																	
Bridge-height restrictions	4	1	4	1	4			X							X		
River dredging and spoils disposal	4	1	1	1	3	X		X						X	X	X	
Disposal of water from dewatering	5	1	5	1	5	X		X		X							
Pollution of ground water (by local spills, leakage, or poor disposal practices)	4	1	4	1	4			X						X	X		
Existing utility conduits (gas, water, power, telephone)	5	1	3	1	5					X	X			X	X		X
Existing foundations (buildings, bridges)	5	5	5	5	5					X	X			X	X		X
Existing tunnels	5	1	2	1	5	X			X	X	X			X	X		X
Existing wells (completed in)	3	1	2	1	5					X	X			X	X		X
Multiple well completion (open to more than one aquifer)	2	1	2	1	2			X					X	X	X		
Induced infiltration caused by dewatering	2	1	3	1	3	X		X		X	X		X	X	X		X
Poor core recovery	4	1	2	1	4	X		X						X	X		X
Surficial Deposits																	
Natural																	
Boulders in drift	2							X		X	X			X	X		
Inhomogeneity of drift or buried valley fill	5							X		X	X		X	X	X		
Lake sand and compressible silt bodies	3							X		X			X	X	X		
Extensive sand and gravel bodies	3							X		X			X	X	X		
Sand lenses in till	4							X					X	X	X		
Fractured till	4							X					X	X	X		
Manmade																	
Unstable slopes in open cuts	3					X		X		X				X	X	X	X
Settlement of structures	3					X			X	X				X	X		X
Subsidence due to dewatering	3					X			X	X			X	X	X		X
Bedrock																	
Natural																	
Plunge pools and pot holes in river bottom[2]		1	1	1	2			X		X				X	X		
Buried drift-filled valleys		4	4	4	4				X	X	X		X	X	X		X
Tunnels and caves		1	2	1	5			X						X	X		X
Extensive fracturing and jointing		2	5	2	2			X		X			X	X	X		X
Random occurrence of fractures, joints, faults, or soft zones		3	5	3	3	X				X	X		X	X	X		
Solution cavities along fractures or joints		1	5	1	2					X			X	X	X		
Iron-stained or cemented layers		1	1	1	5			X		X	X		X	X	X		
Green shaly-sand layer in upper part of unit		1	1	1	5			X		X	X		X	X	X		
Shale and siltstone layers in lower part of unit		1	1	1	5			X		X	X		X	X	X		
Incoherent when wet (material may flow)		2	1	2	4	X			X	X	X			X	X	X	
Bearing strength too low for use as tunnel roof		4	2	5	3	X			X	X	X			X	X	X	X
Manmade																	
Susceptibility to tunnel collapse or minor failure when dry		1	1	2	3	X		X		X				X			X
Susceptibility to tunnel collapse or major failure when flooded (by ground water)		2	1	3	5	X			X	X				X	X		X
Fissures and voids caused by dewatering		2	2	2	4	X			X	X				X	X	X	X
Dewatering wells pump sand		1	1	1	3	X		X					X	X	X		X
Floor upheaval (sand boils) due to artesian pressure below excavation		1	1	1	2	X		X		X	X			X	X	X	
Tunnel enhancement features																	
Shallow depth	5	4	3	2	2		X					X	X	X	X		
Ease of access from river valley	5	1	5	5	5		X					X		X	X		
Ease of excavation	2	2	1	2	5		X					X		X	X		
Ability to stand unlined where dry	2	4	5	4	4		X					X		X	X		
Ease of dewatering	3	1	4	1	4		X					X	X	X	X		
Strata nearly flat lying	1	4	4	4	4		X					X		X	X		
Normal homogeneity of material	1	4	4	4	4		X					X	X	X	X		
Natural roof forming strata above	1	1	2	5	5		X					X		X	X		
Relatively impermeable overlying bedrock layers	1	1	4	3	4		X						X	X	X		
Relatively impermeable underlying bedrock layers	2	2	4	1	2		X						X	X	X		

[1] Ranked by probability of occurrence on an arbitrary scale of 1 to 5: 1=improbable, 5=highly probable.
[2] Significant to foundation piers where bridges connect tunnels.

The significance and relative probability of occurrence of many of the factors related to tunnel construction are shown in table 8. The probability rankings and significance indicators are judgmental on the part of the authors and are based largely on a general knowledge of the rock formations in the Twin Cities area.

HYDRAULIC PROPERTIES AND TUNNELING CONSTRAINTS

By
Eric L. Madsen and Ralph F. Norvitch
1979

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GEOLOGIC AND HYDROLOGIC ASPECTS OF TUNNELING IN THE TWIN CITIES AREA, MINNESOTA