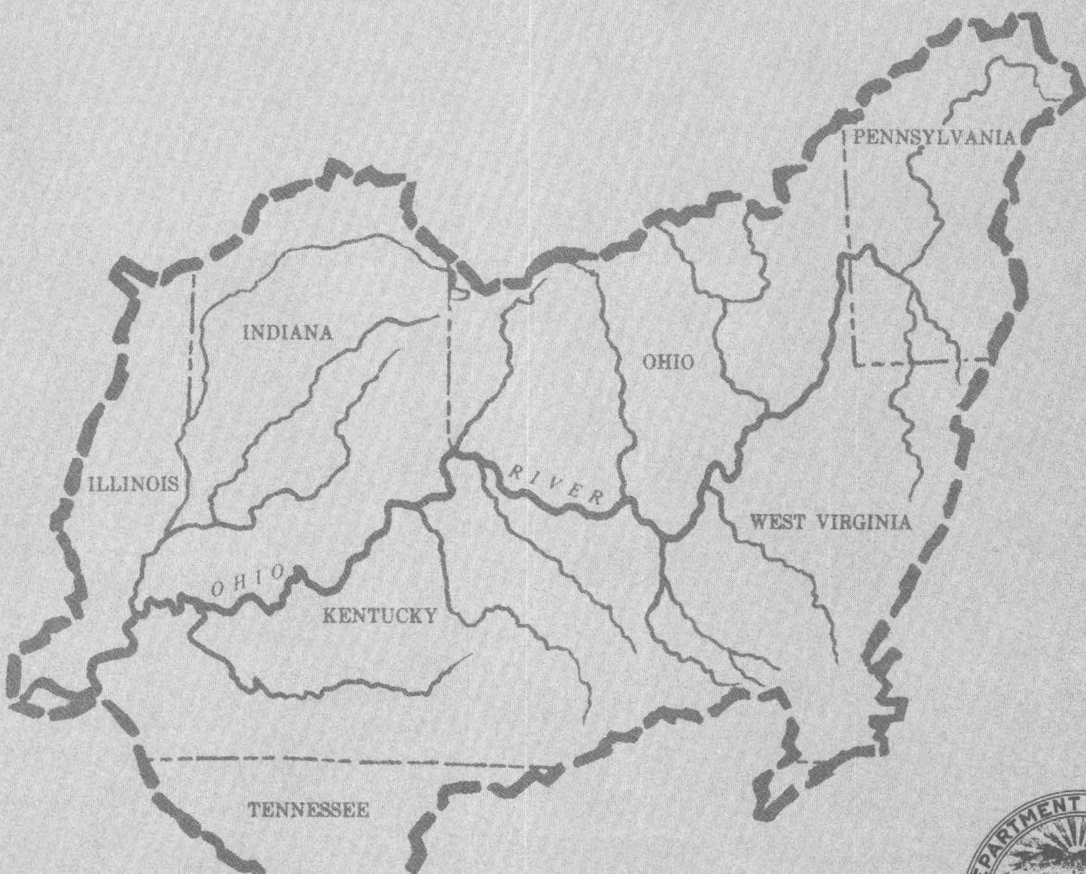
Summary Appraisals of the Nation's Ground-Water Resources—Ohio Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-A



Summary Appraisals of the Nation's Ground-Water Resources — Ohio Region

By RICHARD M. BLOYD, JR.

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Ground-water development and management opportunities in the region

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By Richard M. Bloyd, Jr.

ABSTRACT

Ground water in the Ohio Region is a large, important, and manageable resource that should have a significant role in regional water development.

On the basis of a comparison of ground-water withdrawals with estimated ground-water recharge, it appears that the ground-water resources of the Ohio Region probably will not be used at full potential under existing development plans. Annual ground-water use (1960) by municipalities and rural residents was about 1,000 million gallons per day. Average annual regional ground-water recharge is about 35,000 million gallons per day. Therefore, base-year (1960) municipal and rural ground-water use is only about 3 percent of recharge. Annual regionwide ground-water use (1965) by industry also is only about 3 percent of recharge.

Not all ground water in storage is recoverable for development, but estimates of the amounts that can be obtained from storage, under specified conditions, are calculated to show the magnitude of water that is available. Total potable ground water available from storage in the outwash and alluvial aquifers in the Ohio River valley and the subbasins is about 23,000 billion gallons. This about four times the flood-control storage of all Ohio Region Corps of Engineers reservoirs constructed, under construction, or in advance planning as of July 1965. Approximately 85,000 billion gallons of potable ground water is available from storage in the region in aquifers other than the outwash and alluvial aquifers. This is about 20 percent of estimated storage in Lake Ontario.

About 5 percent of the region has ground-water resources capable of supplying more than local needs. For example, under certain specified conditions the excess of ground-water recharge over base-year (1960) ground-water use is available for 22 million additional people in the Wabash subbasin; for 4, 1.5, and 12 million additional people, respectively, in the Miami, lower Scioto, and Allegheny subbasins; for 5 million additional people in the Ohio River valley; or for equivalent quantities of water supply for industrial or agricultural expansion or other use. A reasonable assumption is that much of the available ground water in these areas can be pumped and transported to reasonably distant points of need.

The Wabash and White subbasins probably have the highest potential of all Ohio River subbasins for additional ground-water development. About 30,000 billion gallons, or about 28 percent of the total potable ground water available from storage in the Ohio Region, is in storage in these subbasins. Estimated average annual ground-water recharge in the Wabash and White subbasins is 7,300 million gallons per day. Annual ground-water use (1960) by municipalities and rural residents of the subbasins of about 220 million gallons per day is only about 3 percent of estimated annual ground-water recharge and only about 0.3 percent of the potable ground water in storage in the subbasins. Also, many high-yield aquifers are present and offer excellent reservoir-manipulation possibilities in conjunction with existing and planned surface reservoirs.

Practically all areas of high population density in the Ohio Region have the potential for development of ground-water resources. The Indianapolis, Ind., area probably has the highest potential.

Assuming that future population growth will be heaviest in the areas paralleling the interstate highway system, much of the increased water demand associated with these growth areas can be supplied by ground water. The areas of population growth in Indiana and southwestern and south-central Ohio are especially well situated in terms of potential ground-water supplies.

Underground space in the Ohio Region, consisting of natural pore spaces and fractures in rocks and sediments, can be considered a regional resource in the sense that it can be included in regional water-pollution control or waste-disposal plans. Much of this space is already occupied by ground water or other fluids which must be displaced for any alternate use. There is a potential for underground waste storage in practically the entire Ohio Region.

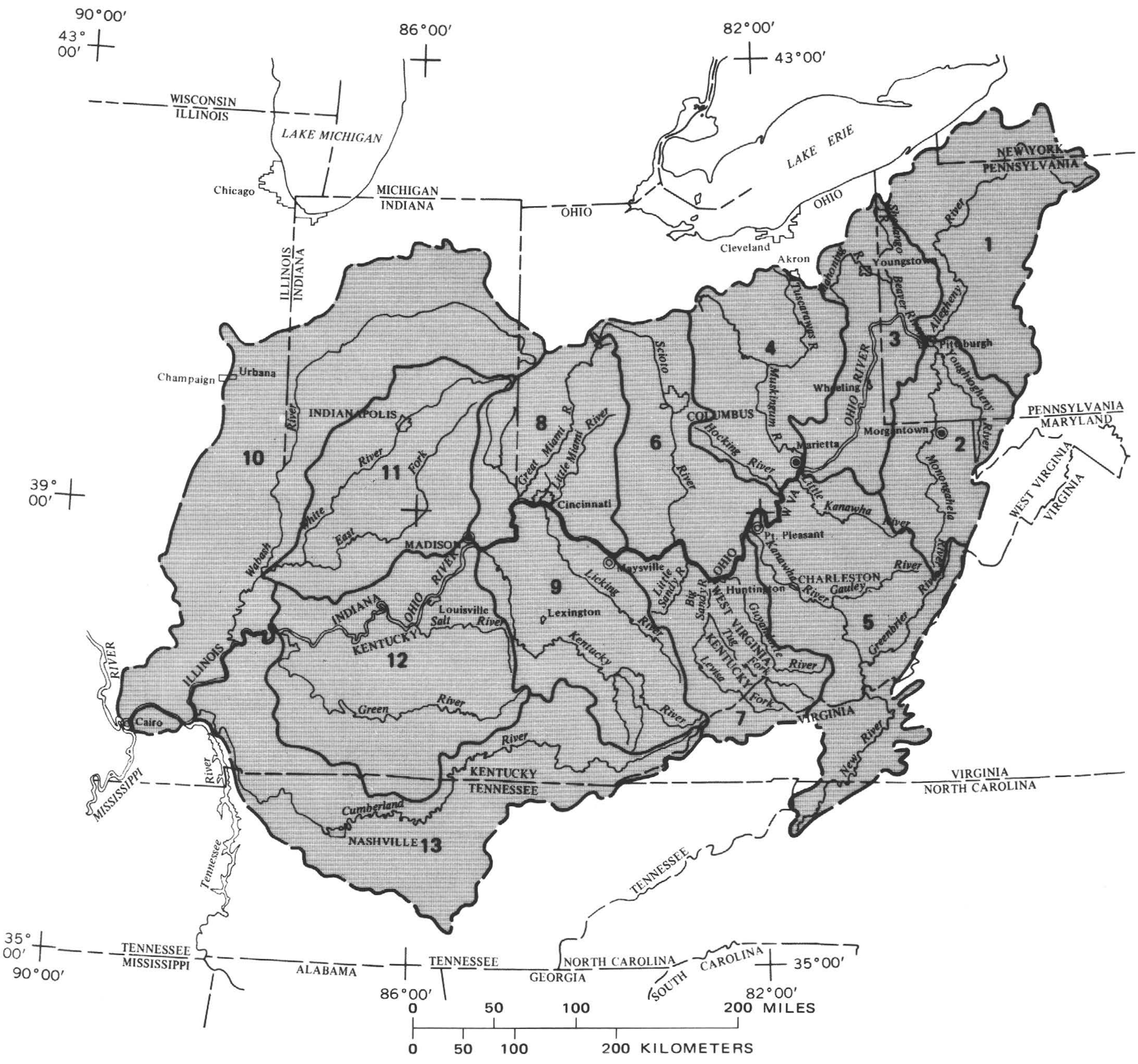
Rapid advance of techniques in ground-water hydrology during recent years has provided methods which the hydrologist can use for evaluating planned ground-water development. Therefore, the manager can resolve the inherent problems that historically have bred caution when this part of our total water resource was considered for development.

INTRODUCTION

The purpose of this study was to make a broad-perspective analysis of the ground-water resources of the Ohio Region and thereby to demonstrate that the region's ground water is a large, important, and manageable resource that should have a significant role in regional water development. The analysis includes assessment of the significance of the ground-water resource in regional water supply, of quantities of ground water available, of quality of the water, of present and potential problems associated with its use, and of additional information needed for planning and efficient development.

This report emphasizes the role of ground water in water-resource planning and presents hydrologic and related information which will permit incorporation of the ground-water resource in the overall resource development and water-management scheme for the region.

The boundaries of the study area are the surface-water drainage boundaries of the Ohio River basin, exclusive of the Tennessee River drainage. For study purposes, the area was divided into 13 subbasins (fig. 1).



SUBBASINS IN THE OHIO REGION

1. Allegheny
2. Monongahela
3. Upper Ohio River
4. Muskingum
5. Kanawha-Little Kanawha
6. Scioto
7. Big and Little Sandy-Guyandotte
8. Great and Little Miami
9. Licking-Kentucky
10. Wabash
11. White
12. Green-Salt-Lower Ohio River
13. Cumberland

FIGURE 1. — Subbasins in the Ohio Region described in this report.

INTEGRATING GROUND WATER INTO WATER RESOURCE PLANNING

Historically, the tendency of planners has been to ignore or minimize the role of ground water, even though the subsurface system offers many advantages, including versatility. This tendency may have been justified in some situations because the ground-water resource could not be precisely evaluated in terms of availability, quality, cost of development, or effects of development on surface-water supplies. The water pumped from wells must be balanced by a change in water distribution within the total hydrologic system. Therefore, when ground water is used, one or more of the following conditions may arise and cause alarm: The ground-water supply is progressively depleted, the streamflow is reduced, and (or) the water quality is changed.

Rapid advance of techniques in ground-water hydrology during recent years has provided methods which the hydrologist can use for evaluating planned ground-water development. Therefore, the manager can resolve the inherent problems that historically have bred caution when this part of our total water resource was considered for development.

TECHNOLOGY AVAILABLE FOR PLANNING

An impressive array of tools is available for planning the development of ground water, for analyzing the alternative conjunctive or independent use of ground water and surface water, and for optimizing management objectives within specified physical, economic, and social constraints. Mathematical and statistical models have achieved greater utility since computers have become available. Models have been developed that simulate the ground-water regimen and predict the effects of stresses imposed by man.

Electric analog models have been used to describe ground-water hydrology in a variety of geologic environments in many places throughout the United States and in several foreign countries. The resistor-capacitor network of an analog permits display of a visual analogy of the ground-water system, which is especially useful in describing and understanding ground-water systems. Analogs also can predict the effects of stresses that may be applied to hydrologic systems.

Also, mathematical models have been programed in digital computers, providing yet another valuable tool to the hydrologist and water manager. Sufficient experience in digital modeling has been acquired to show that ground-water systems can be accurately simulated and the models manipulated to predict changes, both in quantity of flow and in water quality, resulting from natural phenomena and from man's activities. For example, it is possible to describe changes in water quality that might result from changes in water-management practices or to predict the fate of liquid contaminants intentionally or accidentally released to the environment. Thus, a pilot project now underway in the Arkansas River valley of Colorado will be used there to describe and predict on a monthly basis changes in salinity in the alluvial aquifer and in the adjacent stream.

The results of a model analysis are no more reliable than the data used to construct the model. However, with adequate geologic and hydrologic investigation, aided by models, ground water can be integrated into water-resource planning with a high degree of assurance and effectiveness.

DATA REQUIREMENTS FOR PLANNING

The data requirements for a planning study of a ground-water system depend upon the size and hydrologic complexity of the area and upon the types of water problems. Some planning studies need large-scale model analyses, whereas others require only a descriptive evaluation of the hydrologic data.

In determining the types of ground-water information to be presented in this report, it was assumed that water-resource planners in the Ohio Region will use systems engineering for establishing and implementing an optimal water-resource development scheme. What types of information are necessary for the application of the various methods, such as modeling and simulation, comprising the systems method?

The first type of information needed is that which helps the planner to determine whether the ground-water resource in the Ohio Region is available at points of need, or can be transported, in sufficient quantity at the right time and in acceptable quality to warrant further consideration.

The second type of information needed is estimates of the total resource available for allocation and of the individual demands among competing activities. Such estimates, along with cost estimates associated with allocation of the resource, are pertinent to the application of optimization techniques, such as linear programming. In the typical linear programming approach, available resources are allocated in an optimal manner among various competing activities.

This report provides an estimate of the total ground-water resource available. Initial estimates of water demand are available in a comprehensive survey study of the basin (U.S. Army Corps of Engineers, 1969). The present report includes no estimates of costs for supplying ground water because costs vary widely from place to place and from use to use. However, when specific requirements and a time frame are specified, cost estimates can be developed.

The third type of information needed is estimates of storage coefficients, transmissivities, aquifer boundaries, and the degree of connection between streams and aquifers. Such information is basic to the application of system modeling and simulation.

Many pertinent data, already available, are summarized in following sections of this report.

ASSESSING THE GROUND-WATER RESOURCE

GEOLOGIC FRAMEWORK

Alluvium, outwash, and glaciofluvial deposits constitute the most productive part of the ground-water system in the Ohio Region. Streams draining the glaciated part of the region (fig. 2), have redeposited size-sorted glacial sediments well beyond the southernmost encroachment of the glacial ice during the Ice Age and, thus, have helped to create highly permeable aquifers in widespread parts of the region.

Holocene alluvium, consisting of silt, sand, and gravel, is present in the lower reaches of the major tributary valleys south of the Ohio River. In general, these sediments are finer grained and less permeable than the glaciofluvial deposits.

Outwash, composed predominantly of sand and gravel deposited by melt-water streams, is generally highly permeable and is an excellent source of water. Outwash deposits are most extensive in valleys of major tributaries within the limits of glaciation. Where these deposits are present beyond the limits of glaciation, they occur as valley-train deposits.

Glaciofluvial deposits, which are a mixture of Pleistocene outwash deposits and Holocene alluvium, occur along many of the major tributary streams and in the Ohio River valley. These deposits are generally excellent sources of water.

Till is the principal type of glacial deposit present in the region. It is a heterogeneous mixture of clay, silt, sand, and gravel, has very low water-transmitting ability, and therefore is a relatively poor source of water. Moraines of unsorted till deposits form low ridges along former fronts of glacial ice sheets.

The Ohio Region is underlain by a series of bedrock units that vary greatly in thickness and in hydrologic characteristics and that range in age from Precambrian to Tertiary (fig. 3). The most conspicuous large features of the bedrock are the Appalachian and Illinois basins (fig. 3). These two basins are separated from each other and from the Michigan basin to the north by the Cincinnati, Findlay, and Kankakee arches and the Nashville dome (fig. 3). By envisioning a two-bowled candy dish with the bowls separated but molded together by rims, one can envisiõn the general configuration of the surface of the basement rock in the Ohio Region.

The slope on the surface of the basement complex, from the arch areas toward the Appalachian and Illinois basins, is the central feature controlling the slope or dip of the younger bedrock unit overlying the basement. This general slope or dip is modified locally in areas of folding and faulting. The general dip on the bedrock aquifers east of the Nashville dome and Findlay arch is toward the low point of the Appalachian basement-rock depression; the dip on the bedrock aquifers west of the Findlay arch and south of the Kankakee arch is toward the low point of the Illinois basement-rock depression.

AQUIFER CHARACTERISTICS

Another important step in assessing the ground-water resource in the Ohio Region and in describing the aquifer system is the specification of values for aquifer characteristics, such as hydraulic conductivity and storage coefficient. Knowledge of aquifer characteristics makes it possible to delineate the various aquifers in the basin and to analyze the dynamic processes of ground-water movement.

Hydraulic conductivity, which is a unit measure of the ability of an aquifer to transmit water, depends primarily on the nature of the pore space in the aquifer and on the type of fluid occupying the space. In general, the greater the hydraulic conductivity, the greater is the ability of the aquifer to transmit water.

Transmissivity is a measure of the gross ability of the aquifer to transmit water. It is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer.

The storage coefficient is the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head. In a confined water body the water derived from storage with decline in head comes from expansion of the water and from compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined water body, the amount of water derived from storage by expansion of the water or by compression of the aquifer is generally negligible compared to that involved in gravity drainage or filling of pores. In an unconfined water body the storage coefficient corresponds to the specific yield and is generally greater than 0.01.

Estimated aquifer characteristics for aquifers in the Ohio Region are listed in table 1. The estimates are derived from previous studies and are considered to be sufficiently accurate for areal application.

STREAM-AQUIFER INTERRELATION

The purposes of this section of the report are to show that generally there is hydraulic connection between the ground-water and surface-water systems and to develop data needed in defining the ground-water resources of the region.

Hydraulic connection between the ground-water and surface-water systems and a vast supply of ground-water

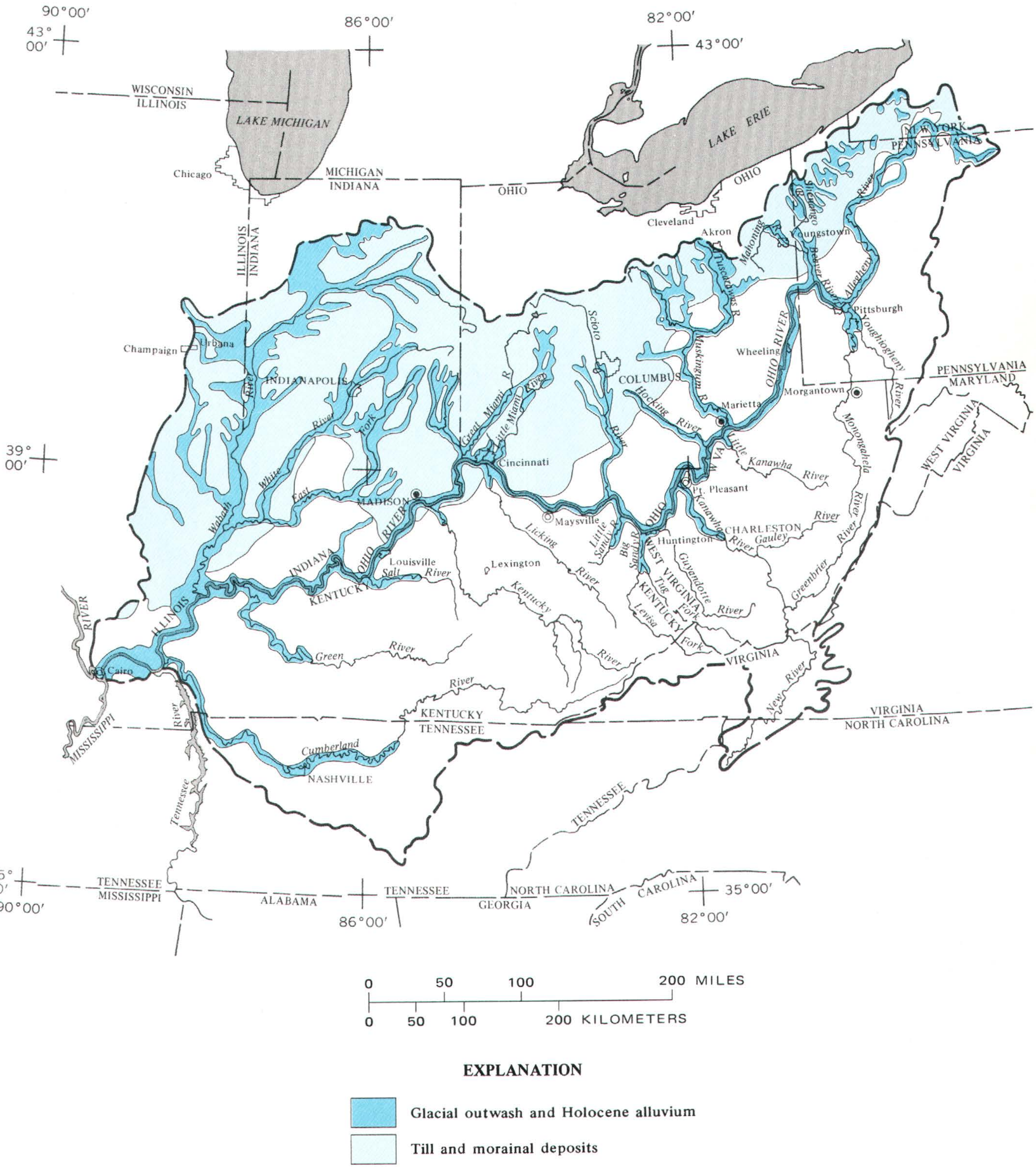
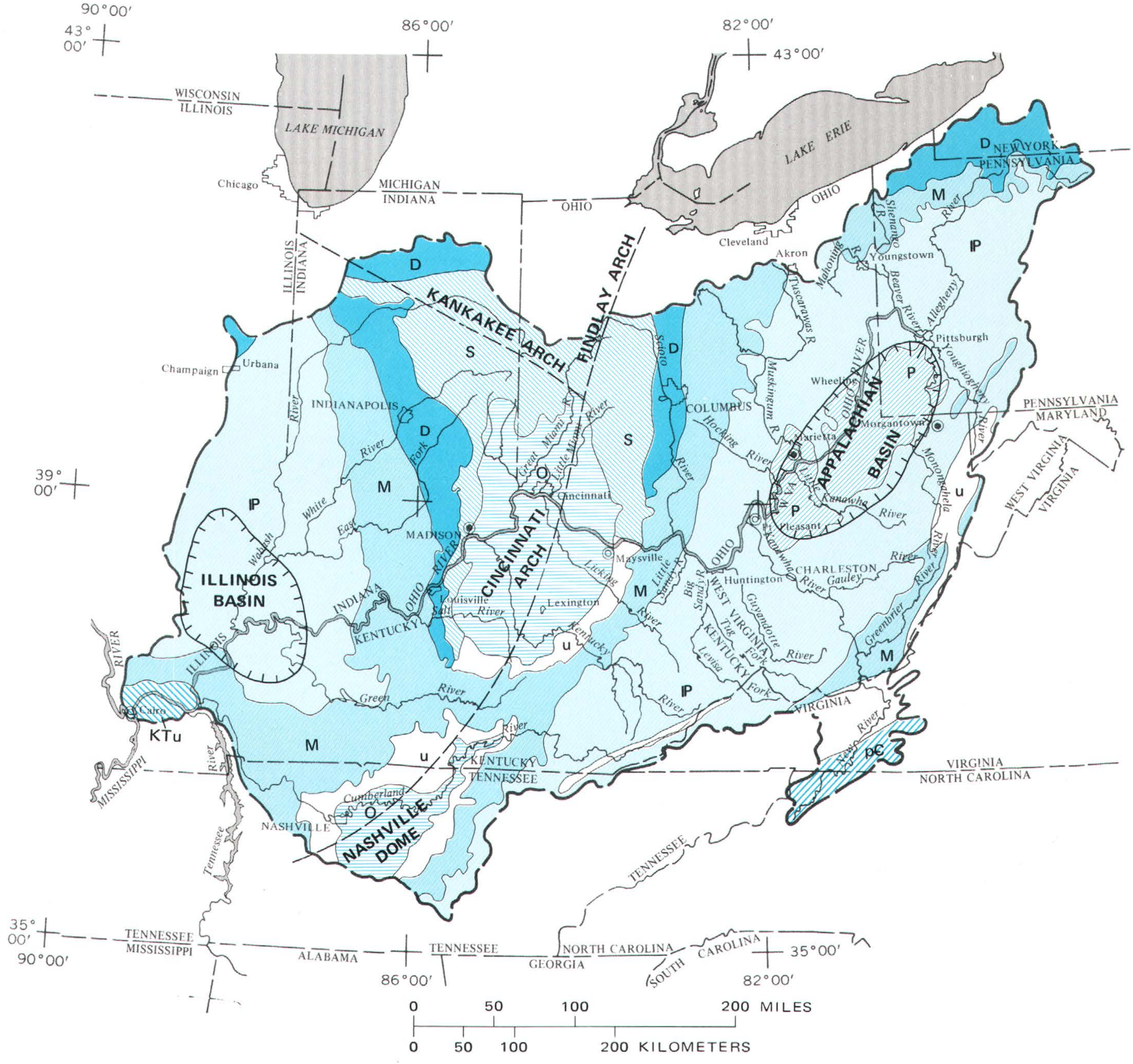


FIGURE 2. — Distribution of unconsolidated sediments.

in the region indicate a potential for large economic benefits. Nature has provided a natural subsurface multipurpose multireservoir system. Not only has nature supplied the system, she has tailored the system with a hydraulic link with the surface-water system.

Because of the interaction between ground water and surface water, streamflow data for nonregulated perennial streams can be used to estimate ground-water discharge to streams, average annual ground-water discharge and recharge, and the hydraulic conductivity of



EXPLANATION

KTu	Cretaceous and Tertiary undivided	MESOZOIC
P	Permian and Pennsylvanian	PALEOZOIC
IP	Pennsylvanian	PALEOZOIC
M	Mississippian	PALEOZOIC
D	Devonian	PALEOZOIC
S	Silurian	PALEOZOIC
O	Ordovician	PALEOZOIC
u	Paleozoic rocks undivided*	PALEOZOIC
pC	Precambrian	

——— Contact

*Includes Cambrian through Mississippian rocks in Valley and Ridge province; Upper Ordovician, Silurian, and Devonian rocks along southern rim of Cincinnati arch; Silurian, Devonian, and Lower Mississippian rocks around Nashville dome; and Devonian and Mississippian rocks along Pine Mountain thrust fault.

FIGURE 3. — Major subdivisions of the bedrock in the Ohio Region. Adopted from U.S. Geological Survey (1932).

TABLE 1. — *Characteristics of the consolidated and unconsolidated aquifers in the Ohio Region and ranking of aquifers in order of decreasing transmissivity*

Aquifer	Hydraulic conductivity (gpd/ft²)	Storage coefficient or specific yield
1. Mad River alluvial aquifer	4,000–4,500	0.25
2. Ohio River valley outwash and alluvial aquifer	400–8,400	0.05–0.20
3. Miami River, Scioto River, Upper Muskingum River, and Whitewater River alluvial aquifers	2,500–3,000	.15– .20
4. Allegheny, Lower Wabash, and White River alluvial aquifers	2,000	.15– .20
5. Hocking River, Lower Muskingum River, and Upper Wabash River alluvial aquifers	1,500–2,000	.15– .20
6. Beaver River alluvial aquifer and alluvial aquifers in the minor tributaries north of the Ohio River	500–1,000	.15
7. Alluvial aquifers in the major tributaries south of the Ohio River	500	.10
8. Mississippian bedrock aquifer (Green River Basin)	>20	.01– .05
9. Mississippian bedrock aquifer with glacial cover	>20	.01– .05
10. Pennsylvanian bedrock (Allegheny and Pottsville Formations)	>20	.01– .05
11. Pennsylvanian bedrock with glacial cover	>20	.01– .05
12. Silurian bedrock with glacial cover	>20	.01– .05
13. Pennsylvanian bedrock (Conemaugh Formation)	>20	.01– .05
14. Pennsylvanian and Permian bedrock (Dunkard Group)	>20	.01– .05
15. Ordovician bedrock with glacial cover	>20	.01– .05
16. Silurian bedrock	>20	.01– .05
17. Mississippian bedrock	>20	.01– .05
18. Pennsylvanian bedrock (Monongahela Formation)	>20	.01– .05
19. Devonian bedrock with glacial cover	>20	.01– .05
20. Ordovician and undifferentiated Paleozoic rocks	>20	.01– .05
21. Devonian bedrock	>20	.01– .05

aquifers that are in hydraulic connection with streams. Data from U.S. Geological Survey offices in the region were used for such purposes in the study., Most of the data were obtained from streamgage network evaluation studies made in each State. In these evaluation studies, a streamflow-frequency distribution was computed for each unregulated gaging site where at least 10 years of streamflow records were available. Except for the data on Ohio, which was adjusted to the standard period 1931–60 (Cross, 1968), the data used in this report were not adjusted to a common base period because of the short time allotted to the study. Even though the streamflow data were not adjusted to the standard base period, they can be used effectively in this general appraisal study as long as possible deficiencies in the data are kept in mind.

Variation in the overall regimen of streamflow can be depicted with a cumulative frequency curve constructed on the basis of the amount of time during which specific values of streamflow are equaled or exceeded. The water in streams during periods of high flow is derived from both direct surface runoff and ground-water discharge. As streamflow decreases, the percentage of streamflow derived from direct surface runoff also decreases.

The flow equaled or exceeded 90 percent of the time, or the 90-percent flow, generally is assumed to be all ground-water discharge. Because the choice is based on empirical studies and because ground-water discharge does vary seasonally, arguments have been presented for the choice of different percent flow values. Wyrick and Lloyd (1968, p. H19), mentioned data that indicated that the ground-water component of discharge to streamflow varies from the streamflow exceeded 60 percent of the time to that exceeded 90 percent of the time. Stuart, Schneider, and Crooks (1967, p. 42) showed that, for a stream in southeastern Pennsylvania, the flow exceeded more than about 75 percent of the time is all ground-water discharge.

The approach taken in this study is that two flow-duration parameters define the annual ground-water discharge to streams better than one. This approach is based upon the assumption that seasonal variation in base flow of a perennial stream is caused partly by seasonal variation in vapor discharge from aquifers. Because of the variation in vapor discharge, one parameter is necessary to define the ground-water discharge to streamflow during the season when vapor discharge is at a maximum, and another parameter is necessary for the season when vapor discharge is at a minimum.

Where ground water sustains streamflow in the Ohio Region, the water table in the vicinity of the streams is close to the land surface and is a ready source of moisture for plants. Therefore abundant vegetative growths generally line stream channels. Because vegetation on flood plains is situated between the ground-water-recharge areas and the stream channels or liquid-discharge areas, the vegetation gets "first crack" at the ground water that is enroute to discharge. During summer months, when transpiration is at a maximum, vegetation diverts more ground water to the vapor phase than during winter months when transpiration is at a minimum. This seasonal variation in magnitude of ground-water diversion by plants causes seasonal variation in base flow.

The assumption is made that the 90-percent flow-duration parameter is an indicator of base flow in a stream during that part of the year when ground-water vapor discharge is a maximum and that the 60-percent flow-duration parameter is an indicator during that part of the year when vapor discharge is at a minimum (fig. 4). Although the above choices may not be the "true" values, at least they seem reasonable.

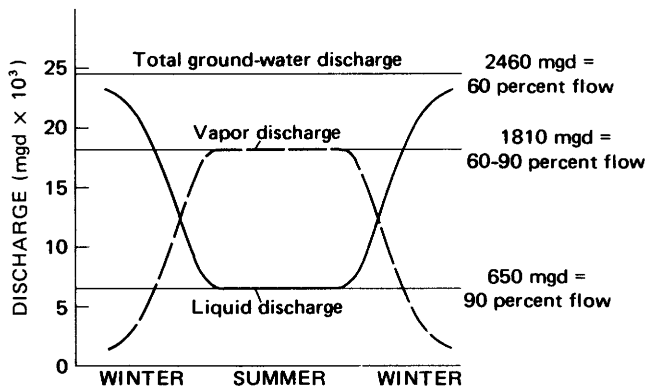


FIGURE 4. — The liquid- and vapor-discharge components and their relation to total ground-water discharge.

Where large reservoirs control flows, downstream flow records are not usable as indices of ground-water discharge. For the Allegheny, Upper Ohio River, Muskingum, Kentucky, and Cumberland subbasins, the 60- and 90-percent flow-duration parameters were determined by averaging values from nonregulated headwater and tributary flow records.

Further discussion on the use of the streamflow data to estimate ground-water recharge is presented in the section "Ground-Water Recharge."

PRECIPITATION — THE SOURCE

Gross water input to the Ohio Region is equal to total basin precipitation. Ground-water inflow to the region, if it occurs, is insignificant relative to total region precipitation.

Although precipitation is areally variable (fig. 5; table 2), average annual precipitation in all parts of the Ohio Region exceeds the national average. Monthly and seasonal variability of precipitation is greatest in the northwestern part of the region and least in the southern part.

On the basis of annual precipitation, average precipitation rates in the various subbasins range from 15,900 mgd (million gallons per day) in the Miami subbasin to about 47,200 mgd in the Cumberland subbasin.

EVAPOTRANSPIRATION—A MAJOR USE

The term "evapotranspiration" refers to the natural processes by which water on and beneath the land surface returns to the atmosphere as water vapor. Evapotranspiration is the largest single component of natural fresh-water discharge from the hydrologic system.

Mean annual lake evaporation is commonly accepted as potential evaporation or the maximum rate at which water can be taken into the atmosphere. It ranges from about 27 inches to about 37 inches in the region (fig. 6).

The type of vegetation and the depth of vegetative root systems in part determines the depth limit from which evapotranspiration can occur. This lower depth limit is not accurately known, but it probably is not more than 15 feet.

Maximum evapotranspiration probably occurs from alluvial aquifers adjacent to gaining reaches of many streams of the region, where water is readily available to the vegetation growing in the highly transmissive alluvial deposits. Evapotranspiration of ground water also occurs in marshlands and in the immediate vicinity of natural lakes fed by ground water.

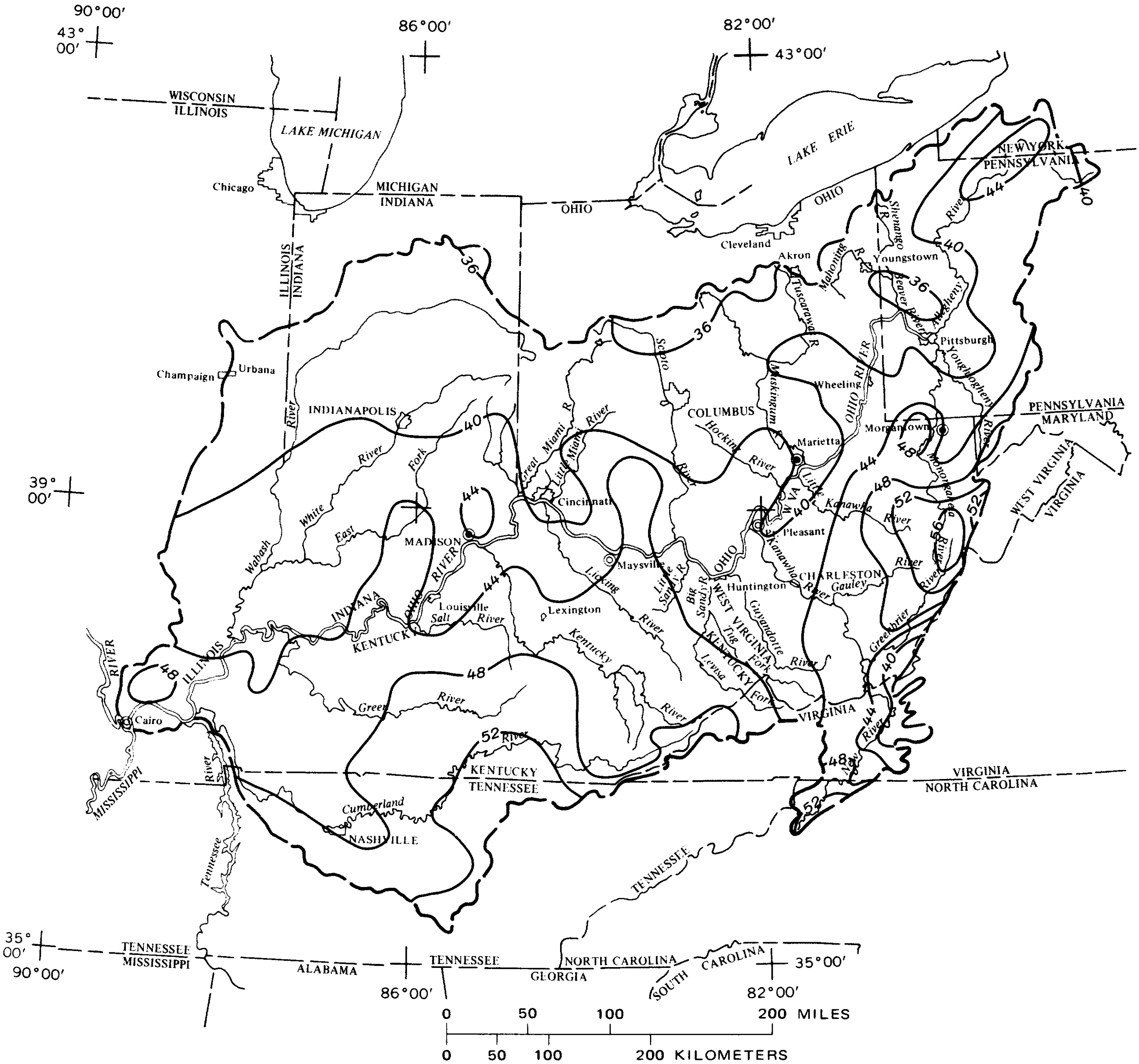
THE SUPPLY

In simple terms, ground water in the region occurs in two zones: the supply of fresh water is at relatively shallow depths; the deeper zone contains a large supply of water of poorer quality. Hopkins (1966) mapped the interface between fresh and saline water in some parts of the region.

Although not all ground water in storage is recoverable by development, estimates of the amounts that can be obtained from storage, under specified conditions, are calculated to show the magnitude of water that is available.

FRESH WATER

For purposes of assessing the ground water available from storage, fresh water is defined as water containing less than 1,000 mg/l (milligrams per liter) dissolved solids. The definition is arbitrary because some waters with less than 1,000 mg/l dissolved solids are not potable. On the other hand, some municipal water systems in the Southwestern United States deliver water that has dissolved solids exceeding 2,000 mg/l. The Public Health Service specifies 500 mg/l as the desirable upper limit of dissolved solids in drinking water. Most waters can be treated to remove undesirable constituents at a cost. Therefore, in this report, all water is considered to be a resource, and it becomes a planning or management decision whether a given supply is potable or is usable only for other purposes.



EXPLANATION

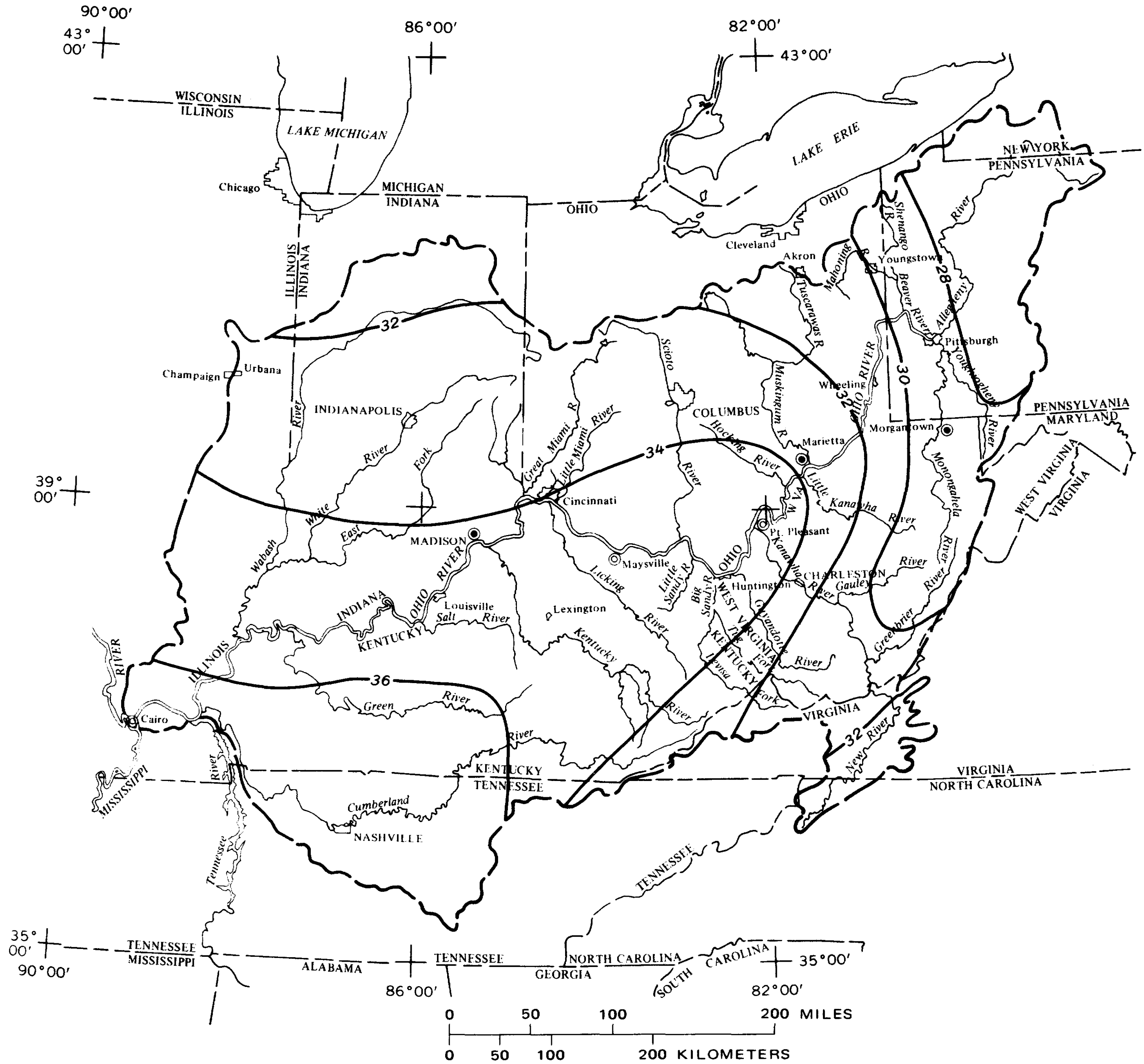
40

Line of equal average annual precipitation, in inches

FIGURE 5. — Average annual precipitation, in inches (U.S. Department of Commerce, Environmental Science Services Administration, 1968).

Three categories of storage were specified for the purpose of computing the amount of potable ground water available from storage in the Ohio Region. They are (1) storage in the outwash and alluvial aquifer in the Ohio River valley, (2) storage in the outwash and alluvial aquifers in the various subbasins, and (3) storage in all other aquifers.

For making calculations of ground water available from storage, the simplifying assumption was made that all the outwash and alluvial aquifers in the Ohio Region are unconfined. In calculating the ground-water available from storage in an unconfined aquifer, the surface area of the aquifer, the saturated thickness of the aquifer, and the specific yield of the aquifer are needed. The areas of aquifers were estimated from geologic maps. Lithologic well logs and water levels in wells were used to



EXPLANATION

—— 32 ——
Line of equal estimated mean annual lake evaporation, in inches

FIGURE 6. — Estimated mean annual lake evaporation, in inches (U.S. Dept. of Commerce, Environmental Science Services Admin., 1968).

estimate the saturated aquifer thickness — the lithologic logs to estimate formation thickness, and water levels in wells to define the zone of saturation. Much of the information on aquifer thickness is from Walker (1957) and Cross and Schemel (1956). Aquifer specific yields and storage coefficients are from aquifer tests.

Estimated amount of water available from storage in the outwash and alluvial aquifer in the Ohio River valley is about 4,500 billion gallons (table 3). About 60 percent of the water is in storage along the lower 200-mile reach of the river. The computed value of available stored water is crude but reasonable. The purpose of the com-

TABLE 2. — *Estimated average annual subbasin precipitation*

No. (in fig. 1) Subbasin	Estimated annual precipitation (in/yr)	Subbasin area (sq mi)	Estimated precipitation (mgd)[1]
1. Allegheny	42.0	11,500	23,000
2. Monongahela	47.0	7,200	16,100
3. Upper Ohio River	40.0	8,400	16,000
4. Muskingum	39.5	9,250	17,400
5. Kanawha–Little Kanawha	44.5	14,750	31,300
6. Scioto	39.5	9,150	17,200
7. Big and Little Sandy–Guyandotte	44.0	8,100	17,000
8. Great and Little Miami	38.5	8,650	15,900
9. Licking-Kentucky	45.0	11,250	24,100
10. Wabash	40.0	23,000	43,800
11. White	42.0	12,500	25,000
12. Green–Salt–Lower Ohio River	48.0	16,350	37,400
13. Cumberland	49.0	20,250	47,200

[1]mgd, million gallons per day.

TABLE 3. — *Calculation of potable water available from storage in the outwash and alluvial aquifer in the Ohio River valley*

Reach of river	Length of reach (miles)	Average aquifer width (ft)	Saturated aquifer thickness (ft)	Saturated aquifer volume (billion cu ft)	Specific yield	Stored ground water: Billions of cubic feet	Stored ground water: Billions of gallons
Pittsburgh to Beaver river	25.5	4,000	50	25	0.20	5	37
Beaver River to Ohio-Pennsylvania boundary	14.5	4,000	50	15	.20	3	22
Ohio-Pennsylvania boundary to Wellsburg	34.0	4,200	50	40	.20	8	60
Wellsburg to Captina	38.0	3,700	45	35	.20	7	52
Captina to Friendly	30.0	3,700	25	15	.20	3	22
Friendly to Muskingum River	30.0	4,700	35	25	.20	5	37
Muskingum River to Washington Bottom	22.5	6,300	35	25	.20	5	37
Washington Bottom to Mason	55.5	4,700	30	40	.15	6	45
Mason to Glenwood	36.5	7,400	35	50	.10	5	37
Glenwood to Big Sandy River	30.5	5,800	15	15	.05	1	7
Big Sandy River to Greenup	19.0	7,900	40	30	.05	2	15
Greenup to Portsmouth	20.5	8,400	40	35	.10	4	30
Portsmouth to Cincinnati	113.5	5,300	50	160	.20	32	239
Cincinnati to Warsaw	59.0	7,100	60	135	.10	14	105
Warsaw to Madison	28.5	6,800	60	60	.20	12	90
Madison to Charleston	31.5	5,300	60	55	.20	11	82
Charleston to NE. Louisville	13.0	8,400	70	40	.20	8	60
NE. Louisville to Valley Station	19.5	15,800	60	100	.20	20	150
Valley Station to West Point	8.5	11,600	70	35	.20	7	52
West Point to Brandenburg	16.0	7,400	70	45	.20	9	67
Brandenburg to dam 45	57.0	6,600	70	140	.20	28	209
Dam 45 to Hawesville	21.0	5,800	80	50	.20	10	75
Hawesville to Lewisport	14.0	10,000	70	50	.15	8	60
Lewisport to NE. Owensboro	15.0	18,200	70	100	.10	10	75
NE. Owensboro to dam 47	25.0	31,200	100	410	.10	41	307
Dam 47 to Henderson	26.0	35,400	70	340	.20	68	509
Henderson to Mississippi River	175.5	20,600	70	1,340	.20	270	2,020
Total						602	4,501

putations is to help planners assess the approximate magnitude of the ground-water resource, rather than to present precise figures.

About 18,300 billion gallons of water is available from storage in the outwash and alluvial aquifers in the subbasins (table 4). The amount ranges from 45 billion gallons in the Kanawha subbasin to 7,100 billion gallons in the Wabash subbasin. The estimates are considered to be conservative, especially those for some areas of higher potential yield. A conservative approach was taken because of the significant areal variations in the saturated thickness of the alluvial and outwash aquifers and because of the paucity of data on the thickness of alluvial sediments for some locations.

TABLE 4. — *Calculation of water available from storage in the outwash and alluvial aquifers in the subbasins*

No. (in fig. 1)	Subbasin	Surface area of outwash and alluvium (sq mi)	Assumed saturated thickness (ft)	Saturated volume (billion cu ft)	Assumed specific yield	Stored ground water	
						Billions of cubic feet	Billions of gallons
1.	Allegheny	1,610	25	1,120	0.15	170	1,270
2.	Monongahela	70	25	50	.15	8	60
3.	Upper Ohio River	370	50	515	.15	77	576
4.	Muskingum	1,050	50	1,460	.15	220	1,650
5.	Kanawha-Little Kanawha	90	25	65	.10	6	45
6.	Scioto	490	50	685	.15	100	748
7.	Big and Little Sandy-Guyandotte	310	25	215	.10	22	165
8.	Great and Little Miami	1,010	50	1,410	.20	280	2,090
9.	Licking-Kentucky	120	25	85	.10	8	60
10.	Wabash	3,410	50	4,750	.20	950	7,110
11.	White	1,980	50	2,760	.20	550	4,110
12.	Green-Salt-Lower Ohio River	560	25	390	.10	39	292
13.	Cumberland	290	25	200	.10	20	150
	Total					2,450	18,326

Total water available from storage in the outwash and alluvial aquifers in the Ohio River valley and the subbasins is about 23,000 billion gallons. This volume is about four times the flood-control storage of all Ohio Region Corps of Engineers reservoirs constructed, under construction, or in advance planning as of July 1965. By further comparison, the volume of ground water is about 5 percent of the volume of water in storage in Lake Ontario, based on Bue's estimate (1963, p. 11) of the volume of water in Lake Ontario.

Most of the ground water in the outwash and alluvial aquifers in the Ohio River valley and the subbasins is assumed to be potable. Exceptions are areas where acid mine drainage is prevalent. In such areas, even where the quality of the ground water is not now degraded, future degradation is possible. This is especially true where alluvial aquifers are hydraulically connected with polluted streams. This study does not delineate aquifers affected by acid mine drainage or other pollutants. Such a delineation should be made in subsequent, more intensive subregional studies. Without a delineation, satisfactory estimates of potable ground water available from storage are not possible.

For calculating the amount of water available from storage in the consolidated aquifers and the remaining unconsolidated aquifers of the region, the following simplifying assumptions were made:

1. That the aquifers are now confined but that lowering of water levels into the aquifers will produce unconfined conditions.
2. That a uniform vertical thickness of 250 feet of potable water is present throughout the Ohio Region in these aquifers.
3. That the amount of potable water available from storage in the aquifers is defined by the product of the aquifer surface area, a saturated thickness of 250 feet, and a storage coefficient or specific yield of 0.01.

The assumed 250 feet of saturated thickness is reasonable and probably conservative. Available data on water levels in wells in the region suggest that, in general, the potentiometric head in aquifers — other than the alluvial aquifers — is less than 100 feet below land surface. Feth and others (1965), showed that at depths greater than 500 feet in practically the entire Ohio region the dissolved solids in ground water is in excess of 1,000 mg/l. Using 100 feet and 500 feet below land surface as the upper and lower limits of potable water, the maximum saturated thickness in aquifers other than the alluvial aquifers is 400 feet. Such saturated thicknesses are not present everywhere. Actually, in many parts of the region, brine is present at shallow depths. Also, because practically all aquifers considered in this example are confined, the potentiometric head is closer to the land surface than the zone of saturation. The simplifying assumption was made that 250 feet is a reasonable value to use for the saturated thickness of potable water.

The assumed storage coefficient of 0.01 also is reasonable and probably conservative. As long as the aquifers are confined, the storage coefficient may range from 0.001 to 0.0001 or less. As the water levels are lowered into the aquifers to produce unconfined conditions, the storage coefficient probably increases and may range from 0.01 to 0.05 or more. In line with the other simplifying assumptions, the use of a constant storage coefficient of 0.01 seems justified.

On the basis of these assumptions, approximately 85,000 billion gallons of potable water is estimated to be available from storage in the Ohio Region in aquifers other than the outwash and alluvial aquifers. This amount is about four times the estimated water available from storage in the outwash and alluvial aquifers (tables 3, 4) and equivalent to about 20 percent of the volume of water in Lake Ontario.

SALINE WATER

Saline ground water is present throughout the Ohio Region. As shown by Feth and others (1965), the dissolved solids in ground water exceeds 1,000 mg/l at depths greater than 500 feet throughout the region. Salt concentrations in the saline zone range from 1,000 mg/l to considerably more than the 32,000–35,000 mg/l concentration in sea water.

The largest quantities of saline water, and therefore of equivalent storage volume in the saline zone, are in the Illinois and Appalachian basins. In these basins the depth to basement rock is the greatest in the Ohio Region. Assuming that the basement rock is the bottom of the saline zone, the bottom of the zone in the Illinois basin is about 9,000 feet below sea level; the bottom in the Appalachian basin is about 15,000–21,000 feet below sea level.

The saline zone can be used as a source of water for desalting, especially in areas where fresh-water supplies are small or as a storage reservoir for injection and recovery of fresh water.

UNDERGROUND SPACE

A simple definition of natural underground space might be expressed as the interconnected pore or fracture space into which a fluid can be emplaced. Underground space is not necessarily vacant. It is already occupied by a liquid or gas that must be compressed or displaced in order to use the space. That part of underground space occupied by potable water is evaluated in the section entitled "The Supply." In this section of the report, emphasis is upon unsaturated underground space at shallow depths. The presence of large volumes of unsaturated permeable deposits suggests the potential for additional temporary underground storage of potable water.

Geologic data suggest the presence of unsaturated outwash and alluvial sediment thicknesses of from 30 to 70 feet in the Ohio River valley adjacent to the main stem of the Ohio River. Seventy-foot thicknesses are present betweem dam 47 and Henderson (figs. 16, 17). Sixty-foot thicknesses are present between Cincinnati and Madison (figs. 13, 17) and between Brandenburg and Hawesville (fig. 17). Aquifer characteristics suggest that the sediments are permeable in all these reaches.

A gross estimate of the unsaturated volume in the above three reaches is 125 billion cubic feet; approximately 68 billion cubic feet is present between dam 47 and Henderson. Even if only one-half of the volume can be artificially recharged, temporary storage is available for approximately 450 billion gallons of water. Lesser volumes of unsaturated sediments and storage are present in other parts of the Ohio River valley.

Only a small potential exists for temporary storage water in other unsaturated geologic units in the region. The low relative permeability of the glacial till probably precludes the use of this unit. The small volumes of unsaturated alluvium in the various subbasins probably makes their use unfeasible. The consolidated aquifers are, for the most part, confined and already saturated, so that pressure effects of artificial recharge probably preclude their use.

DEFINING WATER FLOW THROUGH THE SYSTEM

Except for the almost stagnant brine in the deeper zone, most ground water in the Ohio Region flows through the porous rock stratum or aquifer system of the region from place of intake or recharge to place of discharge. The rate of flow under natural conditions generally ranges from a few tens of feet to a few hundreds of feet per year.

The recharge area for a consolidated or bedrock aquifer in the region is assumed to be the outcrop area of the aquifer; or, if the aquifer is covered with glacial or alluvial deposits, the recharge area is assumed to be the subcrop area underlying the glacial or alluvial deposits. The subcrop area underlying perennial streams generally is a discharge area. On the basis of these factors, the recharge areas for all bedrock aquifers can be inferred from a detailed geologic map.

Once water enters a consolidated aquifer there are two possible flow paths — the path through the intergranular, or primary, openings called pores and the path through secondary openings, such as rock fractures or solution channels. The intergranular openings generally were formed when the rocks were deposited as sediments. Although compaction and cementation generally occur with time and alter the original size and shape of the primary openings, some pore space generally is available in rocks. Rock fractures and solution channels, which occurred after the original deposition of the rocks, provide additional conduits for ground-water accumulation and movement. The secondary openings generally transmit greater quantities of water at higher rates than the primary openings.

The major discharge areas of the consolidated aquifers in the Ohio Region probably are the Illinois and Appalachian basins and the Ohio River valley. In these areas there is significant vertical ground-water discharge or interaquifer flow. Cartwright (1970, p. 917) used ground-water temperature anomalies in the Illinois basin to calculate the annual vertical ground-water discharge in an 1,800-square-mile area. He concluded that possibly as much as 95 percent of the discharge must be moving upward through vertical fractures or secondary openings.

Recharge to the unconsolidated alluvial and outwash aquifers comes from infiltration of precipitation, from upward interaquifer flow, and from percolation of streamflow from losing streams. In most areas the major source of recharge is precipitation. Under natural conditions practically all the exposed surface areas of the unconsolidated aquifers are recharge areas.

Under present manmade conditions of development, the recharge areas for unconsolidated aquifers encompass a smaller area than under former natural conditions. The unconsolidated alluvial aquifers generally are in the relatively flat stream valleys. The flat terrain favors economic development and habitation by man. As man develops and inhabits the area, some of the previously exposed land surface is covered by pavement and other impervious materials. Therefore, there is a decrease in the recharge area of the unconsolidated aquifers. In some areas of intensive urban and industrial development, almost all ground-water recharge is prevented.

The general direction of ground-water flow in the unconsolidated deposits of the region is toward the streams. As suggested in the section, "Stream-Aquifer Interrelation," the streams of the region are the "sinks" for ground-water discharge. Actually, there is interplay between the surface-water and ground-water systems. One reach of a stream may be a gaining reach, whereas a subsequent reach may be losing. Also, a gaining stream can become a losing stream and a losing stream can become a gaining one as the stream stage changes.

DELINEATION OF AQUIFERS

The aquifer system in the region was subdivided and ranked into 21 major units (table 1). The ranking of the units was made on the basis of the transmissivity of the aquifers in the units. The initial subdivision was made mainly on the basis of geologic age of the various units in the region (fig. 3). Modification of the initial subdivision was made on the basis of streamflow data, and the final refinement was made on the basis of available aquifer-test data.

The highest yielding aquifer in the Ohio Region is the outwash and alluvial aquifer occupying a valley that is incised into the Silurian bedrock system in the Mad River drainage area (fig. 15). Yields of individual wells in this area exceed 1,000 gpm (gallons per minute), and rather extensive development of the ground-water resource has already occurred. For example, in the Dayton, Ohio, area, 110 mgd of ground water was used in 1958. This was about one-fourth of the total ground-water use in the State at that time (Norris and Spieker, 1966).

The outwash and alluvial aquifer in the Ohio River valley is ranked as the second highest yielding aquifer in the region. Aquifer yields in some parts of the valley exceed those of the aquifer in the Mad River drainage, but as an overall unit the aquifer is less productive.

The Mississippian aquifer is the highest yielding bedrock unit in the region. Aquifer yields vary from place to place, but yields to wells are significant in the Green River subbasin, in Indiana and Ohio, and in Pennsylvania, where the unit is covered by glacial drift.

GROUND-WATER RECHARGE

Although various methods are used to determine available ground water in a region, most methods assume that average annual ground-water recharge is the upper limit of ground water perennially available. Assuming such a need for recharge estimates, they are presented in this report, but it should be recognized that not all recharge is necessarily available for use.

The 60-percent flow-duration data were used to make order-of-magnitude estimates of subbasin ground-water recharge (table 5). Assuming that the 60-percent flows are indicators of natural ground-water discharge, they also can be used as indicators of natural ground-water recharge. This assumes that an approximate hydrologic equilibrium must exist between ground water entering and leaving the hydrologic system. Actual ground-water discharge to streams probably is less than that indicated by the 60-percent flow parameter for the Monongahela, Allegheny, and Kanawha Rivers; therefore, ground-water recharge as determined by this parameter (table 5) for those rivers probably should be adjusted downward. The summary of recharge computations (table 5) suggests that recharge in the subbasins may be on the order of 15 percent of the subbasin precipitation. Although for the general purposes of this study no adjustments were made, detailed studies should include more precise estimates of recharge.

PRODUCTIVITY OF AQUIFERS IN THE OHIO REGION

Deutsch, Dove, Jordan, and Wallace (1969) estimated the rates at which aquifers in the Ohio Region can yield water to wells. These estimates, which were adopted in this study, were prepared on the basis of rock type, geologic structure, known well and spring production, low-flow streamflow records, drillers' records, and general knowledge of the local geohydrology.

Both the consolidated and unconsolidated aquifers of the region were classified on an areal basis into the categories of highest, high, intermediate, or low yield. The highest yield category applies to aquifers with a potential yield greater than 500 gpm; the high-yield category, 100–500 gpm; the intermediate-yield category, 25–100 gpm; and the low yield less than 25 gpm. In the Ohio Region the most productive wells are those situated adjacent to major streams and designed to induce flow from the stream to the alluvial ground-water reservoir. Areas ranked in the highest- and high-yield categories (fig. 7) have sufficient ground water for most municipal and industrial water demands. Areas ranked in the

TABLE 5. — *Summary of ground-water recharge computations*

No. (in fig. 1)	Subbasin	Subbasin area (sq mi)	60-percent flow (cfsm)[1]	Estimated ground-water recharge		Percent of subbasin precipitation
				Cfs	Mgd	
1.	Allegheny	11,500	0.55	6,300	4,100	18
2.	Monongahela	7,200	0.63	4,500	2,900	18
3.	Upper Ohio River	8,400	0.28	2,400	1,600	10
4.	Muskingum	9,250	0.27	2,500	1,600	9
5.	Kanawha-Little Kanawha	14,755	---	----	----	16
	Kanawha	12,461	0.58	7,200	4,700	--
	Little Kanawha	2,294	0.29	670	400	--
6.	Scioto	9,150	0.11	1,000	600	3
7.	Big and Little Sandy-Guyandotte	8,100	---	----	----	8
	Big Sandy	4,660	0.23	1,100	700	--
	Little Sandy	1,610	0.16	260	200	--
	Guyandotte	1,830	0.31	570	400	--
8.	Great and Little Miami	8,655	---	----	----	10
	Great Miami	6,276	0.29	1,800	1,200	--
	Little Miami	2,369	0.24	570	400	--
9.	Licking-Kentucky	11,231	---	----	----	5
	Licking	4,185	0.19	800	500	--
	Kentucky	7,046	0.19	1,300	800	--
10.	Wabash	23,000	0.32	7,400	4,800	11
11.	White	12,500	0.31	3,900	2,500	10
12.	Green-Salt-Lower Ohio River	16,350	0.31	5,100	3,300	9
13.	Cumberland	20,250	0.36	7,300	4,700	10
	Total			54,670	35,400	

[1]Cfsm, Cubic feet per second per square mile.

intermediate-yield category are capable of meeting the water demands of many small municipalities or industries. Areas ranked in the low-yield category (fig. 8) are capable in general of meeting only domestic water demands through individual wells.

Approximately 5 percent of the total region is classified in the highest yield category (table 6). Individual wells yield greater than 1,000 gpm in at least eight reaches of the Ohio River main stem and in the Wabash, Scioto, Muskingum, and Allegheny subbasins. Potential extraction rates in excess of 500 gpm are possible from practically the entire Ohio River valley outwash and alluvial aquifer and from parts of the unconsolidated aquifers in all subbasins north of the Ohio River.

WATER-SUPPLY NEEDS

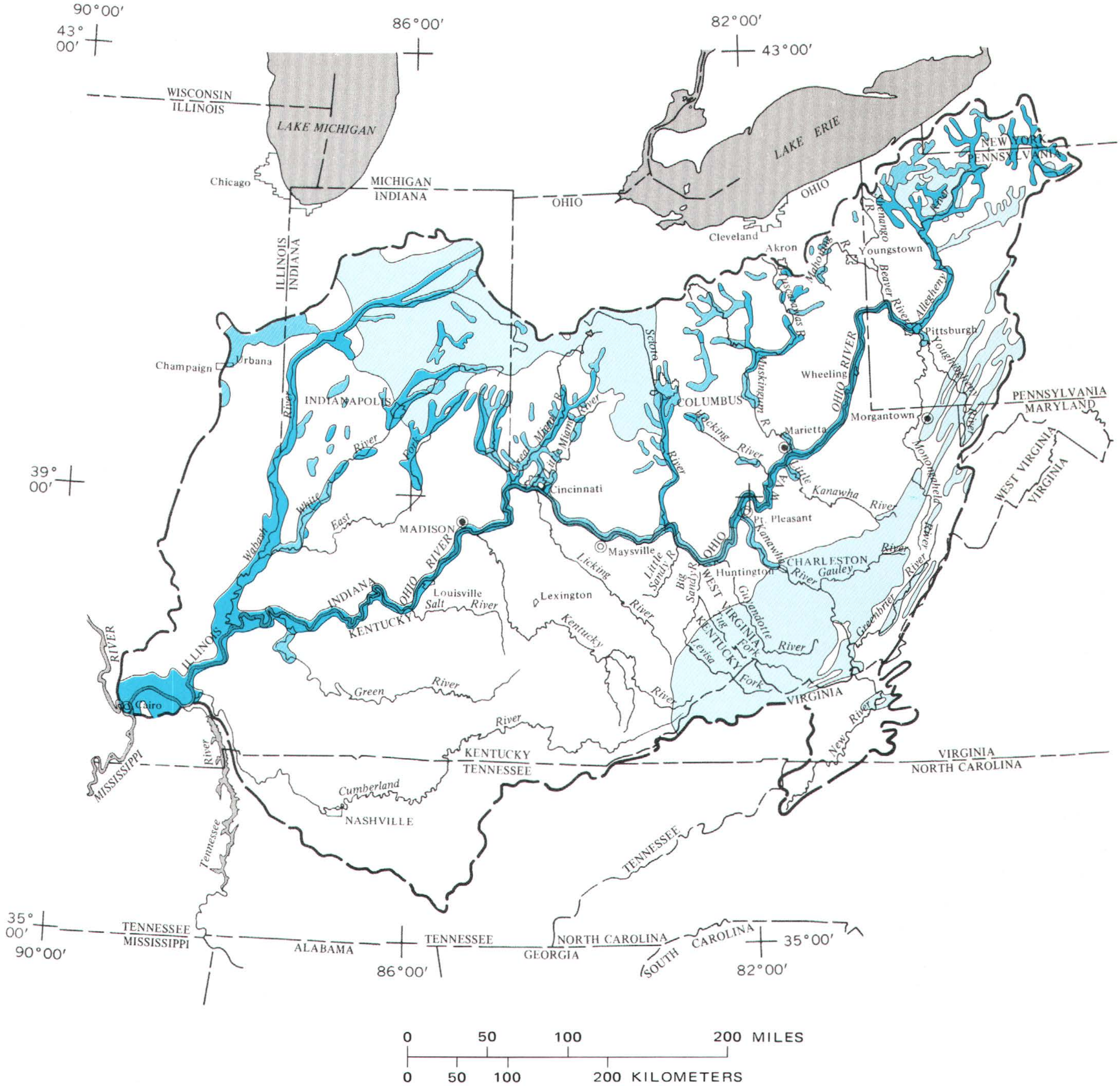
Foregoing information in this report was presented to assist evaluation of the potential of the ground-water supply in the Ohio Region; the next logical step is to consider water demand.

CURRENT NEEDS

Partial estimates for ground-water withdrawals are presented in the "Ohio River Basin Comprehensive Survey." Estimates are presented by subbasin for the base-year (1960) municipal and industrial water use (U.S. Department of the Interior, Federal Water Pollution Control Administration, 1967), and for base-year rural water use (U.S. Army Corps of Engineers, 1968). The estimated base-year municipal water use is by water source so that estimated base-year municipal ground-water use is available. Industrial ground-water use by subbasin is not presented in the above reports. However, Murray (1968) presents basinwide industrial ground-water use for 1965. For the purposes of this report it was assumed that all base-year rural water use was from ground-water sources. This assumption probably is not far in error. The available base-year ground-water-use data were extracted from the reports of the comprehensive survey and from Murray's report and are presented in tabular form (table 7).

PROJECTED NEEDS

The gross demand for water and related functions in the region was estimated by the Corps of Engineers for the years 1980, 2000, and 2020 (table 8). By the year 2020, the total annual surface-water withdrawals in the region, including the nonconsumptive part returned to streams, are projected to be about 64 percent of the average annual volume of streamflow of the Ohio River at its mouth. Excluding the flow volumes from the Tennessee River, the Ohio River streamflow will, by the year 2020, about equal withdrawals in the Ohio Region. Reuse of water, of course, allows for greater use than total flow.

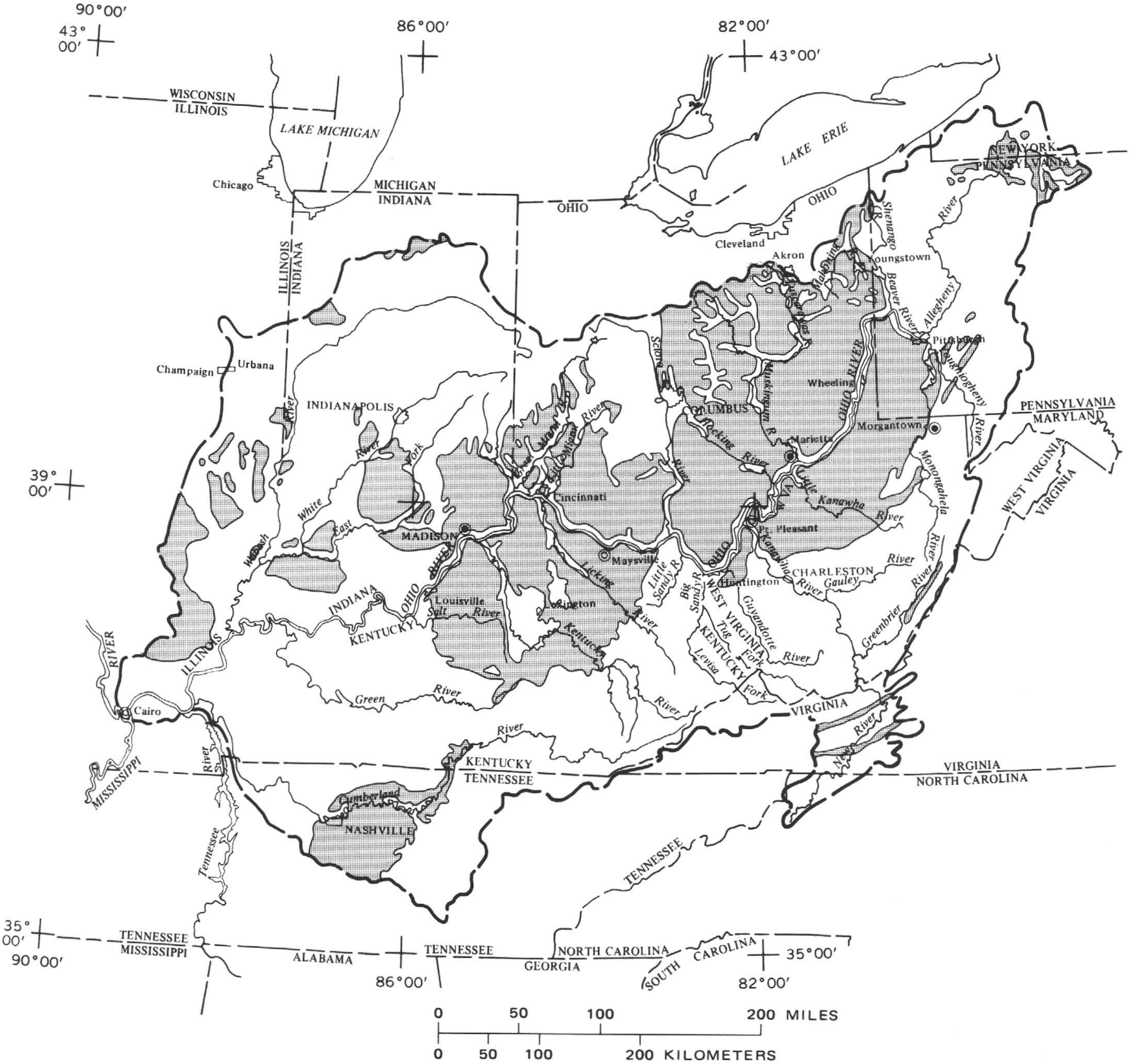


EXPLANATION

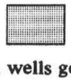
Potential yields to individual wells

- Unconsolidated aquifers, greater than 500 gpm
- Unconsolidated aquifers, 100-500 gpm
- Consolidated aquifers, 100-500 gpm

FIGURE 7. — High-yield sources of ground water.



EXPLANATION



Areas where individual wells generally yield less than 25 gallons per minute

FIGURE 8. — Low-yield sources of ground water.

TABLE 6. — *Classification of subbasin area by potential amounts of ground-water withdrawal*

No. (in fig. 1)	Subbasin	Percent of area: Highest yield	High yield	Intermediate yield	Low yield
1.	Allegheny	8	12	50	30
2.	Monongahela	0	26	49	25
3.	Upper Ohio River	4	1	41	54
4.	Muskingum	2	4	5	89
5.	Kanawha–Little Kanawha	1	35	35	29
6.	Scioto	3	26	6	65
7.	Big and Little Sandy–Guyandotte	2	43	35	20
8.	Great and Little Miami	5	19	19	57
9.	Licking-Kentucky	1	3	42	54
10.	Wabash	12	32	41	15
11.	White	8	16	40	36
12.	Green–Salt–Lower Ohio River	5	1	76	18
13.	Cumberland	4	0	74	22
	Total Ohio basin	5	16	44	35

TABLE 7. — *Base-year (1960) municipal, industrial,*[1] *and rural water use*

NOTE. — Total basin industrial ground-water use (1965) was 930 mgd (Murray, 1968).

Subbasin	Average municipal water use (mgd): Total	Ground water	Surface water	Average industrial use (mgd)	Average rural use (mgd)
Allegheny	215	32	183	278	51
Monongahela	142	4	138	4,718	36
Upper Ohio River	172	60	112	1,608	28
Muskingum	86	50	36	72	53
Kanawha–Little Kanawha	45	10	35	1,477	53
Scioto	81	9	72	57	29
Big and Little Sandy–Guyandotte	16	8	8	51	31
Great and Little Miami	142	128	14	161	45
Licking-Kentucky	35	3	32	3	34
Wabash, White	242	88	154	216	129
Green–Salt–Lower Ohio River	4	1	3	3	22
Cumberland	67	6	61	46	54
Ohio River Huntington	30	4	26	362	--
Ohio River Cincinnati	121	7	114	47	--
Ohio River Louisville	100	11	89	37	--
Ohio River Evansville	46	10	36	27	--
Total	1,544	431	1,113	9,163	565

[1]Industrial water use does not include water withdrawn for electric-power cooling purposes.

Estimates of future subbasin water withdrawals in addition to the base-year (1960) amounts are also presented in the "Ohio River Basin Comprehensive Survey" (U.S. Army Corps of Engineers, 1968). The values presented for the years 1980 and 2020 represent the water required to satisfy projected demands for withdrawal and use in addition to those provided in the base year. Such additional withdrawals are assumed by the Corps of Engineers to be a part of the total water withdrawals, both surface and ground water, required to satisfy municipal and industrial, electric-power cooling, rural community, rural domestic and livestock, and

TABLE 8. — *Estimated gross demand for water in the Ohio Region*

[Data are from the U.S. Army Corps of Engineers (1968). Values are in millions of gallons per day]

Use	Withdrawals in 1965	Total demand		
		Year 1980	Year 2000	Year 2020
Municipal and industrial	11,553	14,035	19,357	28,251
Farm, domestic and livestock	162	168	231	294
Rural, nonfarm domestic	587	673	794	934
Irrigation	46	102	352	682
Electric-power cooling	19,200	29,000	46,000	63,000
Mining	289	511	974	1,894
Total	31,837	44,489	67,708	95,055

TABLE 9. — *Projected ground-water withdrawals for the year 2020, in millions of gallons per day*

No. (in fig. 1)	Subbasin	Ground-water withdrawals 1960		Estimated additional withdrawals for the year 2020[1]	Total withdrawal for the year 2020[2]
		Municipal	Rural		
1.	Allegheny	32	51	120	200
2.	Monongahela	4	36	150	190
3.	Upper Ohio River	60	28	200	290
4.	Muskingum	50	53	110	210
5.	Kanawha–Little Kanawha	10	53	260	320
6.	Scioto	9	29	110	150
7.	Big and Little Sandy–Guyandotte	8	31	60	100
8.	Great and Little Miami	128	45	510	680
9.	Licking-Kentucky	3	34	20	60
10. 11.	Wabash, White	88	129	570	790
12.	Green–Salt–Lower Ohio River	1	22	20	40
13.	Cumberland	6	54	40	100
	Total	399	565	2,170	3,130

[1]Additional ground water required to partially satisfy municipal and industrial, electric-power cooling, rural community, rural domestic and livestock, and irrigation demands.

[2]Summation of estimated municipal and rural ground-water withdrawals in 1960 and estimated additional withdrawals above. Values have been rounded off.

irrigation demands. The estimated allowable ground-water-withdrawal rates for the year 2020 were extracted from the Corps of Engineers' report and are presented in tabular form (table 9) to permit further comparison and discussion.

THE SIGNIFICANCE OF THE SUBSURFACE SYSTEM IN THE OHIO REGION

The foregoing information in the report suggests that the region's ground water is a large natural resource and that there is a demand for such a resource. The next logical step is to show how the ground-water resource might be used and that ideally it can have a significant role in regional water development.

THE POTENTIAL FOR ADDITIONAL DEVELOPMENT

On the basis of a comparison of the projected ground-water withdrawals for the year 2020 with estimated ground-water recharge (table 10), it appears that the ground-water resources of the Ohio Region probably will not be used at full potential under existing development plans. Annual ground-water use (1960) by municipalities and rural residents is about 1,000 mgd (table 7). Average annual regional ground-water recharge is about 35,000 mgd (table 5). Therefore, base-year (1960) municipal and rural ground-water use is only about 3 percent of recharge. Annual regionwide ground-water use (1965) by industry, also, is only about 3 percent of recharge.

The Miami subbasin, which includes the Little Miami River drainage, is the only subbasin with projected total

TABLE 10. — *Comparison of projected ground-water withdrawals with estimated ground-water recharge for the year 2020*

No. (in fig. 1)	Subbasin	Total[1] withdrawal (mgd)	Estimated ground-water recharge (mgd)
1.	Allegheny	200	4,100
2.	Monongahela	190	2,900
3.	Upper Ohio River	290	1,600
4.	Muskingum	210	1,600
5.	Kanawha-Little Kanawha	320	5,100
6.	Scioto	150	600
7.	Big and Little Sandy–Guyandotte	100	1,300
8.	Great and Little Miami	680	1,600
9.	Licking-Kentucky	60	1,300
10.	Wabash	790	4,800
11.	White		2,500
12.	Green–Salt–Lower Ohio River	40	3,300
13.	Cumberland	100	4,700
14.	Basinwide industrial use	930	----
	Total	4,060	35,400

[1]Summation of estimated municipal and rural ground-water withdrawals in 1960 and estimated additional withdrawals (from table 9).

withdrawal rates greater than 25 percent of annual ground-water-recharge rates. A similar comparison for the Wabash subbasin suggests that plans for development are grossly underestimating the ground-water potential of the Wabash subbasin. This is true even if all the base-year industrial water use is from ground-water sources, which in fact it is not. The ground-water resources of the Allegheny, Monongahela, and Kanawha-Little Kanawha subbasins are also underdeveloped quantitatively, but water-quality considerations may be the controlling factor in these subbasins.

The Wabash and White subbasins probably have the highest potential of all Ohio Region subbasins for additional ground-water development. About 30,000 billion gallons, or about 28 percent of the total potable ground water available from storage in the Ohio Region, is in storage there. Estimated average annual ground-water recharge in the Wabash and White subbasins is about 7,300 mgd (table 5). Annual ground-water use (1960) by municipalities and rural residents of the subbasins of about 220 mgd (table 7) is only about 3 percent of ground-water recharge and about 0.3 percent of the potable ground water available from storage in the subbasins. Also, many high-yield aquifers are present and offer excellent reservoir-manipulation possibilities in conjunction with existing and planned surface reservoirs. Additional evaluation of the available hydrologic data is needed to design an optimal ground-water-development program for the subbasin.

ADVANTAGES FOR MANAGEMENT OF THE SUBSURFACE SYSTEM

Realizing that there is a potential for further ground-water development in the region, the planner ideally should consider utilizing several advantages associated with the subsurface (geologic) system and ground water. A discussion of some of these advantages follows.

One major advantage is the versatility of the subsurface system. The uses of the subsurface system already are diverse. Broadly speaking, however, the uses may be grouped into two categories — the temporary storage of gases and fluids (principally natural gas and fresh water) for later withdrawal and the injection of waste fluids for which withdrawal is not contemplated. These uses are likely to be competing in many parts of the Ohio Region, hence the need for proper planning and water-resource utilization.

Another advantage associated with ground water is that it generally is a renewable resource. In the section entitled "Ground-Water Recharge," estimates of average annual ground-water recharge are given. In addition to this natural recharge, artificial recharge of aquifers is also possible. Aquifer recharge can be induced from surface streams if the aquifer and stream are hydrologically connected. Surface spreading basins can be constructed adjacent to the stream to increase the area over which infiltration can occur. Recharge wells are used where hydrologic connection between aquifer and streams is poor or where land values prohibit land use for infiltration.

Flexibility is possible in the choice of a type of recharge facility. Depending upon the type of site available, reservoirs, ponds, lagoons, ditches, or pits may be utilized.

A very successful surface spreading facility has been in operation in Dayton, Ohio, for many years. The greater part of the Dayton municipal water supply is ground water. Ground-water pumpage in the major well field averages about 40 mgd; peak pumpage has been as high as 90 mgd (Norris and Spieker, 1966, p. 83). This large supply is maintained by artificial recharge of the aquifer with Mad River water. Infiltration ditches and lagoons covering a 20-acre area have been dredged and are flooded periodically when the turbidity of river water is low. The lagoons and ditches are dredged each year to remove bottom-clogging material and, thus, to maintain a high rate of infiltration.

Some of the records on the use of recharge wells are conflicting, and successes as well as failures have been reported. The injection of chlorinated water, free from silt, into a well casing at a rate sufficient to keep the casing full, has yielded the best results. Chlorine helps prevent the growth of soil-clogging micro-organisms. Silt introduced into a well can clog the well perforations or even penetrate the aquifer and reduce its hydraulic conductivity; and introduction of air in the aquifer can also decrease hydraulic conductivity of the aquifer. Incrustations by chemical action can also occur on metal casings where perforations are above the normal water table and exposed to air, where recharge waters are incompatible with the native water, or for other reasons.

Another advantage associated with ground water is that in much of the region the ground-water supply generally is equally available and dependable throughout the year. Because the volumes of the ground-water reservoir and of the water available from storage are vast, the ratio of the annual volume of ground water pumped from a particular reservoir or aquifer to the total volume present is small. Therefore, the supply is not depleted significantly in any one year or even in a series of years.

Another advantage is that the ground-water supply is widely distributed throughout the region. It is not equal everywhere in volume or rate of availability but is almost universally present in some quantity. This is in contrast to surface water which is readily available only in areas adjacent to perennial streams. The fact that ground water is almost universally present makes it an excellent reserve resource. It is available for emergency use during drought periods when surface-water resources are not available. An emergency also could arise from an accidental contamination of surface-water resources. Another emergency could arise in event of war. Therefore, even though the ground-water resource may not be the prime water resource in an area, a knowledge of the potential of the resource is warranted in planning for contingencies.

Ground water generally is not subject to large seasonal changes in temperature, a feature of importance to some industrial water users, such as chemical companies. Seasonal temperature fluctuations generally are greatest at shallow depths. Seasonal temperature fluctuations may amount to only a few degrees in deeper parts of an aquifer.

Of further importance to many water users, ground water generally is uniform in chemical quality, and the quality is not subject to sudden changes or even seasonal changes. Because the volume of ground water in storage is large and because of low velocities associated with ground-water movement, the replacement or turnover of water in storage is slow; therefore, chemical quality and temperature do not fluctuate considerably over short periods of time in most parts of the aquifer.

An advantage to be considered relative to the present-day concern for the environment is that the local environment or ecology is not permanently altered or scarred when ground water is developed properly. Visible evidence of development is generally limited to a pump, pumphouse, and pipeline. If development at the site ceases, the pump, pumphouse, and pipeline can be dismantled, and the environment can readily be restored to its original state.

Another important advantage is that the subsurface system generally is hydrologically connected with the surface-water system. Where the subsurface and surface-water systems are in good hydrologic connection, beneficial manipulation of the subsurface system is possible.

The beneficial manipulation of the ground-water system involves the lowering or raising of ground-water levels in order to regulate the available storage volume in response to time-varying storage requirements. Because the ground-water reservoir or aquifer, just as a surface reservoir, need not be maintained at full storage throughout the year, storage volume can be regulated. The value of the ground-water reservoir can be measured in part by the practicality or feasibility of such regulation.

The feasibility of any manipulation plan depends partly on the benefits derived as compared with detrimental effects. Just as with a surface reservoir, detrimental effects upon the rest of the hydrologic system and upon the local ecology can result because of induced reservoir water-level changes. In considering possible effects, a range of water-level changes for each manipulation scheme can be estimated. The total range of change can be subdivided into a number of intervals or increments. Then the effect on the ecology or environment can be estimated for each incremental change in water level.

The feasibility of any manipulation plan also depends upon the availability of answers to certain basic technical questions, such as:

1. What is the size of the ground-water reservoir or aquifer?
2. Where are the boundaries of the ground-water reservoir?
3. How much is the natural recharge to and natural discharge from the ground-water reservoir?
4. Where are the areas of natural recharge and discharge?
5. At what rate can water be taken from or added to the reservoir?
6. Are there any local geologic or hydrologic conditions that may hinder use of the reservoir?
7. What is the quality of water in storage and what quality changes may occur because of reservoir manipulation?
8. What is the project life of the reservoir?

Answers to many of these questions can be obtained using the information in this and other reports. More specific and definitive answers are possible when specific manipulation plans for specific areas are proposed and considered.

A limiting factor in practically every potential manipulation plan is the rate at which the ground-water reservoir can be artificially recharged. The potential ground-water extraction rates from wells are general indicators of the rates at which the wells can accept water. Theoretically, an aquifer can be recharged using injection wells at the same rate at which water can be withdrawn from the well, under a given head differential. However, the tendency for wells and infiltration facilities to become clogged causes a decrease in recharge rates with time. Therefore, average recharge rates with time probably will be much less than the designed rates.

The sites with the highest potential for beneficial manipulation of available ground-water-storage volume are in and adjacent to the flood plains of the major streams in the region (fig. 2). These areas have relatively thick and permeable aquifers underlying a surface stream or ready source of recharge. The benefits to be derived in utilizing the ground-water reservoirs underlying these areas as part of the proposed basin-wide reservoir system should be considered in any subsequent subregional studies.

With proper planning and proper water-resource utilization the natural advantages of the subsurface system and ground water commonly outweight inherent disadvantages, and ground water ideally should receive full consideration in water planning.

GROUND WATER TO SATISFY LOCAL WATER REQUIREMENTS

An individual well in almost any part of the region will yield enough water to satisfy a domestic water requirement. However, approximately 35 percent of the region (table 6, fig. 8) in general is capable of meeting only a domestic requirement through an individual well.

Disregarding water-quality considerations, approximately 65 percent of the region (table 6) can satisfy water demands of many small municipalities or industries through individual wells. In such areas individual wells generally yield greater than 25 gpm. Also, ground water can be used in meeting recreational demands where a large surface reservoir is not a specific requirement; for example, for small off-stream fishing ponds, swimming pools, or ice-skating rinks.

In order to consider some local problem-solving alternatives, locations of existing and potential water problems (U.S. Army Corps of Engineers, 1968, appendix K) were superimposed on subbasin maps showing locations of existing ground-water use and productivity of aquifers. In almost all these locations the use is for municipal water supply. For illustrative purposes, only the maps for subbasins with a significant number of projected problem areas are presented in this report (figs. 9–17).

As indicated by figures 9–17, many of the potential problem areas and some of the existing problem areas are underlain by high-yield ground-water reservoirs, which could have an important role in areal or local water-resource development plans.

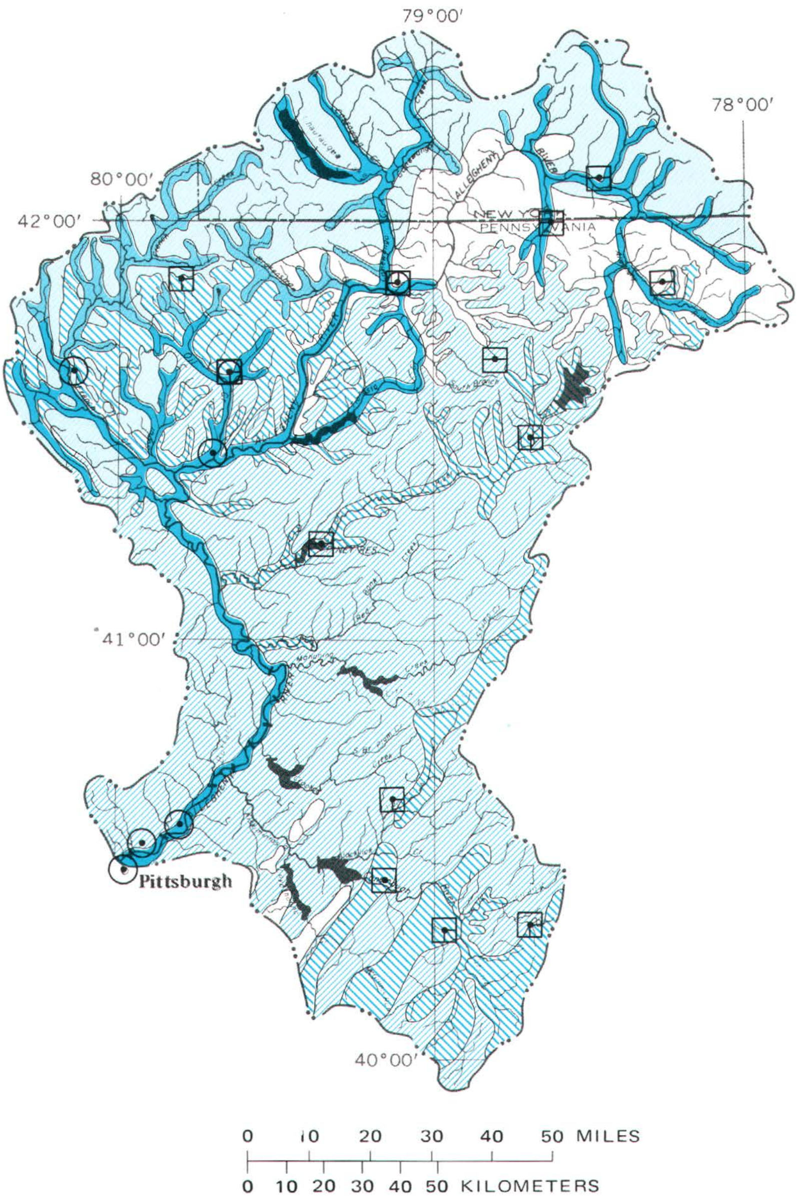
The Miami subbasin, one with highly developed ground-water resources, is indicated as having many potential water-supply problem areas (fig. 13). Most of the problem areas are ones of existing ground-water use and development. The Miami subbasin is the only subbasin in the Ohio Region with projected total withdrawal rates in excess of the subbasin 90-percent flow parameters. Therefore over-development may become a reality. Principles outlined in Spieker's report (1968) should be used for management and development decisions, and other subbasin areas should be studied in like manner.

A comparative illustration shows that more than 140 potential outdoor recreational areas in the Ohio Region are outside the areas of poor sources of ground water (fig. 18). Therefore the ground-water resource is capable of meeting many of the recreational water demands, especially in areas remote from a surface-water source. The U.S. Department of the Interior, Bureau of Outdoor Recreation (1966), determined the potential outdoor recreational areas. An outdoor recreational area is one which meets all or part of demands for swimming, boating, water skiing, picnicking, camping, sightseeing, nature walks, and hiking. In nearly all places ground water can satisfy the water demand associated with the last five of the above demands because the demands are generally small.

The uniform temperature of ground water, especially if the temperature approaches that needed for trout hatcheries, makes the ground-water resource a potentially valuable resource of the sports-fishery industry. The potential value is there because cold-water streams capable of producing or sustaining trout fishing generally are limited to the forested mountainous areas of the Appalachian area. The use of ground water, although it may be expensive, could significantly expand the area in which trout fishing is possible.

GROUND WATER AS A REGIONAL RESOURCE

For ground water to be considered a regional resource, a large supply must be present, a large part of the supply



EXPLANATION

Potential water-supply problem areas

- Present (1972)
- 1980
- 2000
- 2020

Location of known significant municipal ground-water use

Potential well yields

- Unconsolidated aquifers yield greater than 500 gpm
- Unconsolidated aquifers yield 100-500 gpm
- Consolidated aquifers yield 100-500 gpm
- Unconsolidated aquifers yield 25-100 gpm
- Consolidated aquifers yield 25-100 gpm
- Aquifers yield less than 25 gpm

FIGURE 9. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Allegheny subbasin.

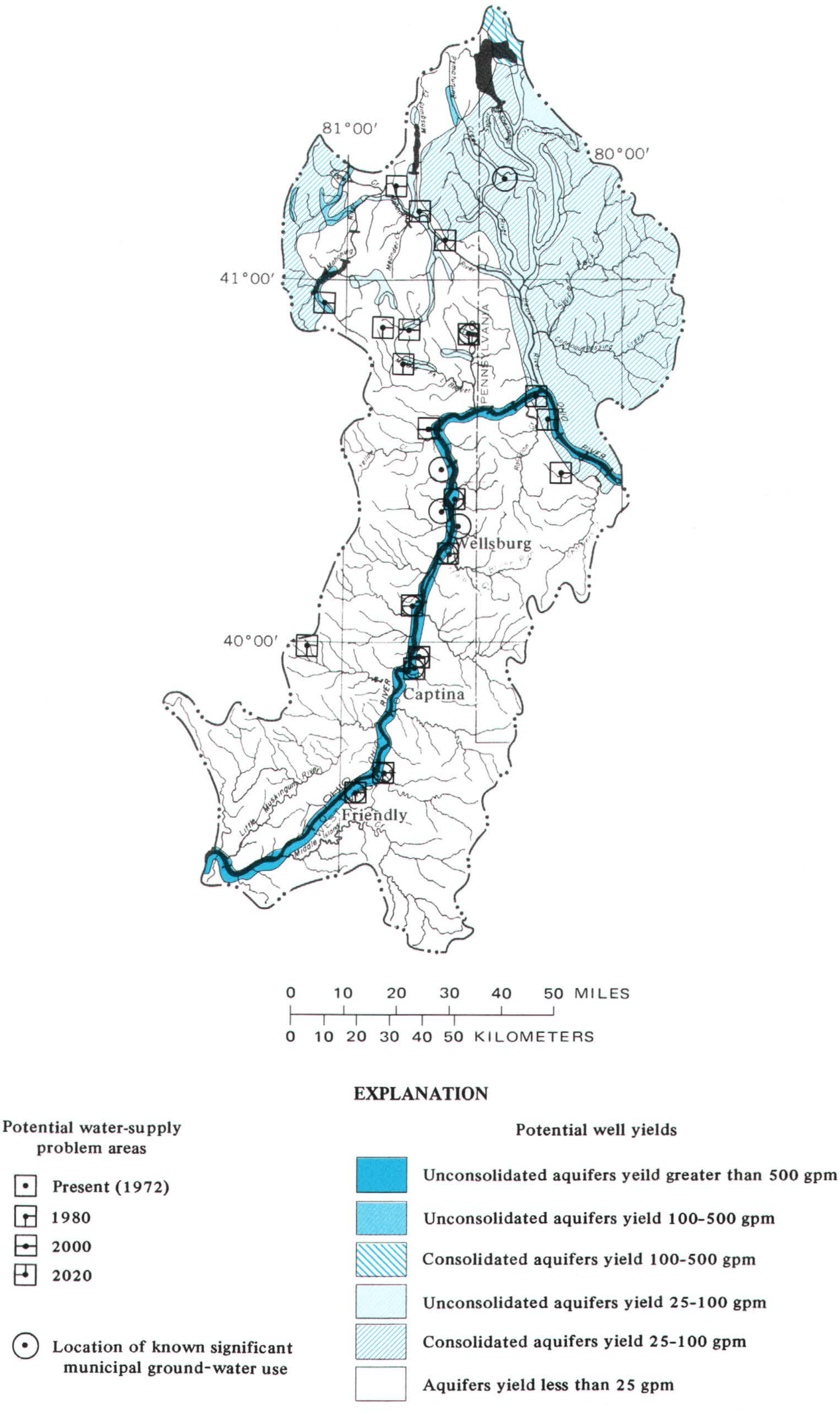


FIGURE 10. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Upper Ohio River subbasin.

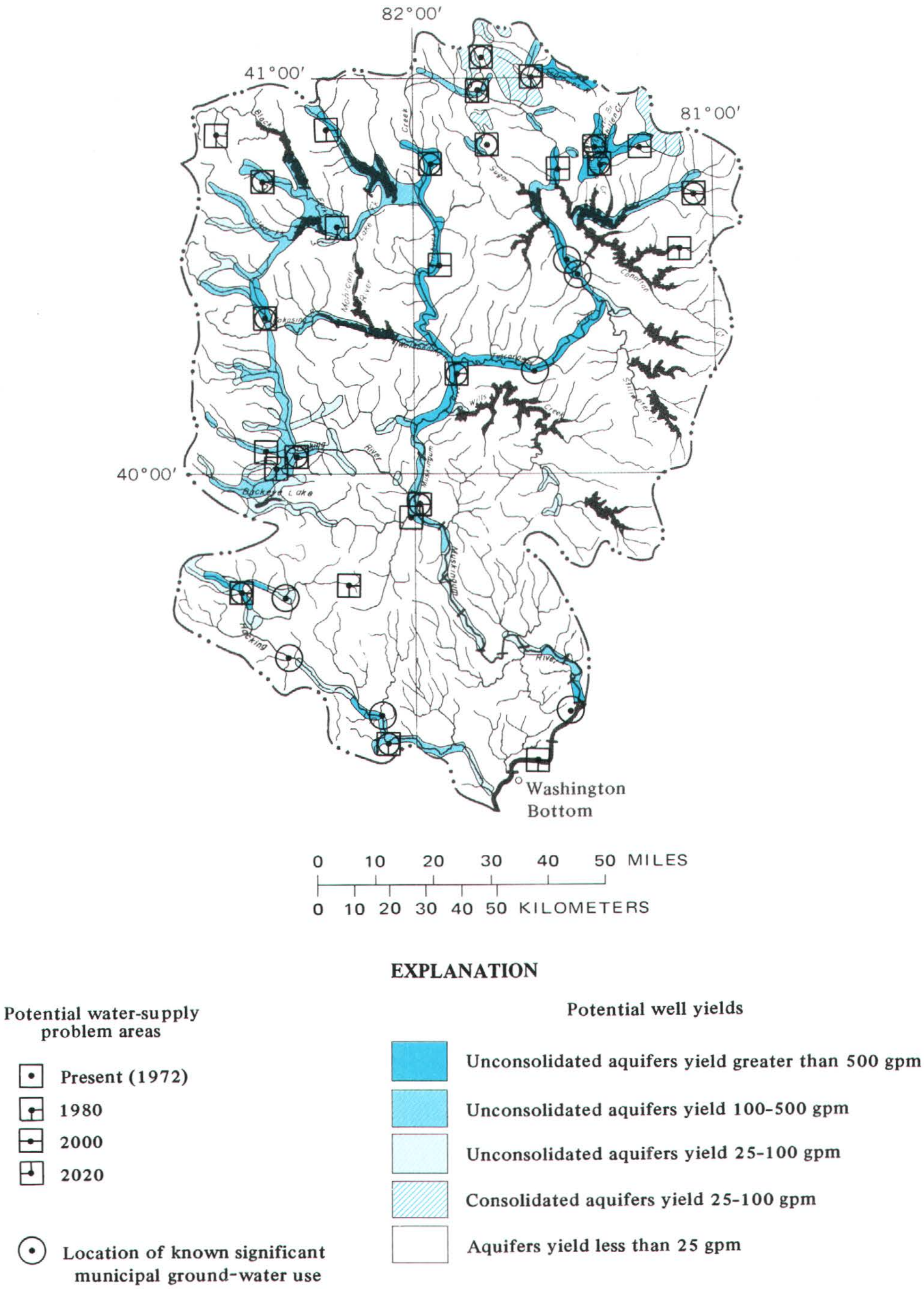


FIGURE 11. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Muskingum subbasin.

must be available, and the supply must be renewable. Unless these criteria are met, large-scale regulation of the subsurface system probably is not warranted.

Specific criteria used in this report to classify the resource as regional are:

1. An unconsolidated aquifer(s) of significant areal extent and a saturated thickness of at least 50 feet must be present.
2. The aquifer(s) must have a potential to yield greater than 500 gpm to individual wells.
3. Surface water must be available for artificial recharge of the aquifer(s).

The ensuing discussion assumes that necessary legislation and land acquisition are possible if development of ground water is feasible. Also, all water referred to is assumed to be potable.

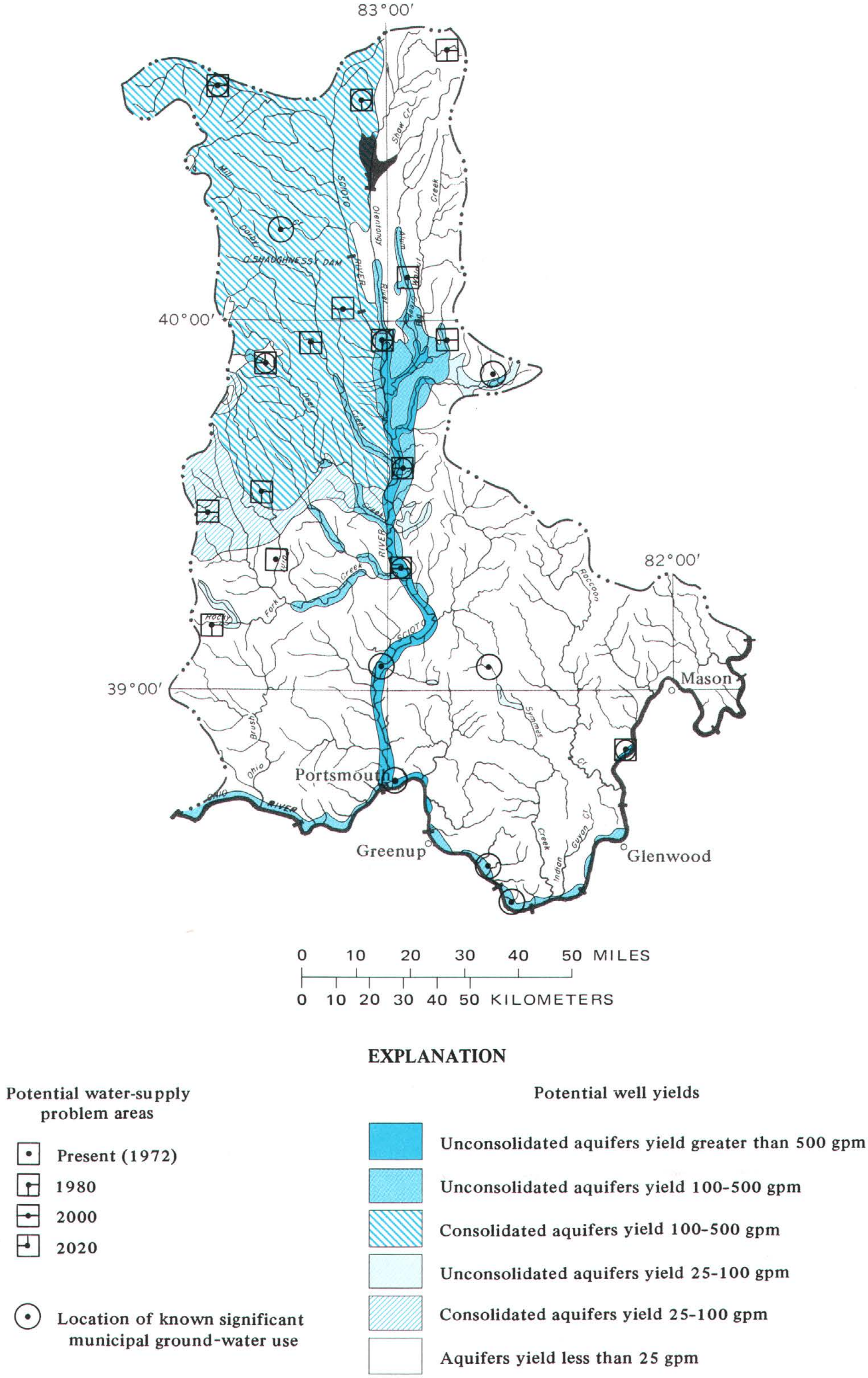


FIGURE 12. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Scioto subbasin.

The above criteria are satisfied in approximately 5 percent of the region in that part underlain by unconsolidated aquifers with the potential to yield greater than 500 gpm to individual wells. The area in the Allegheny subbasin underlain by outwash and alluvial aquifers is included even though the available data

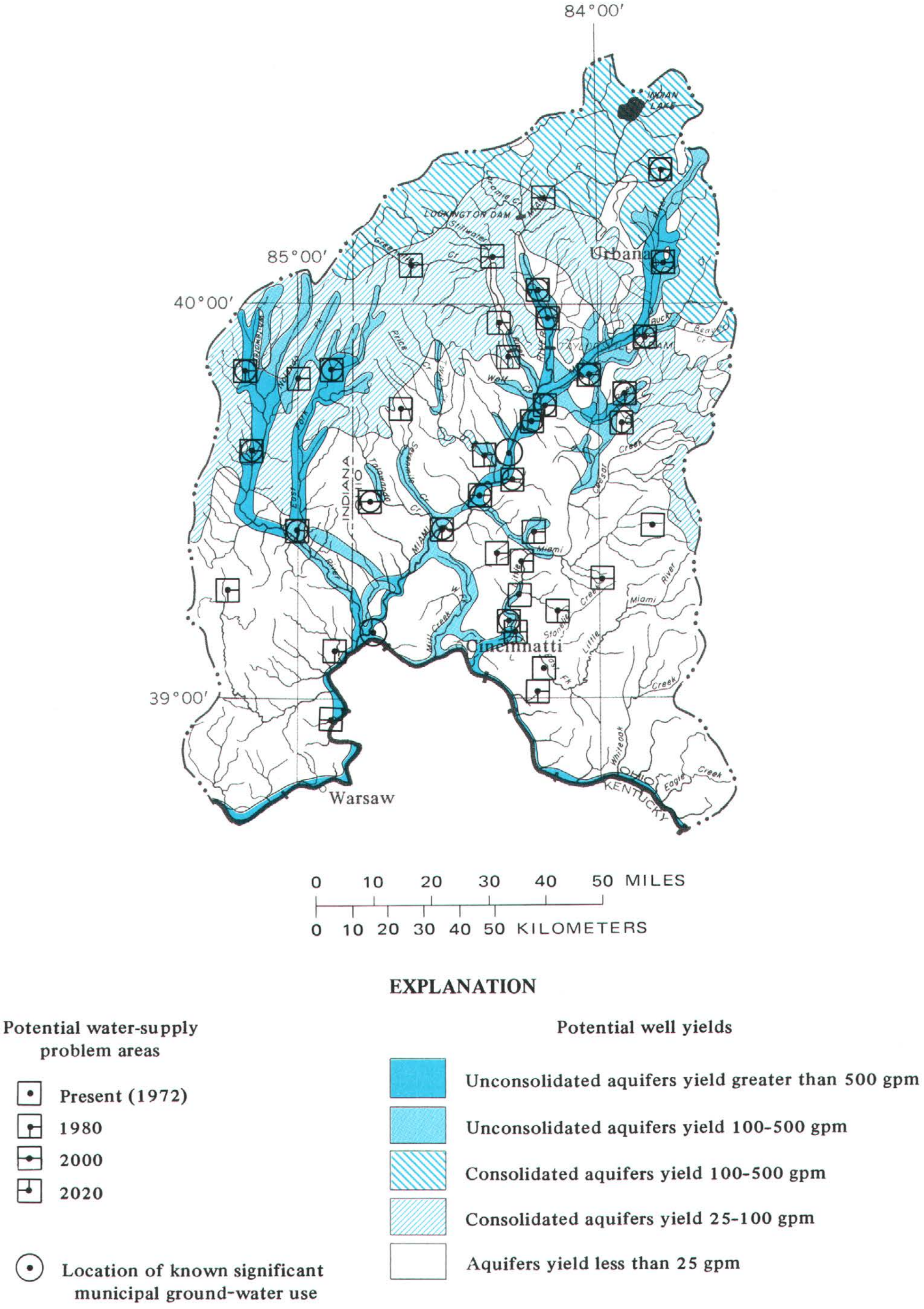


FIGURE 13. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Great and Little Miami subbasin.

suggest a saturated thickness of only 25 feet (table 4). This area is included because the available data on aquifer thickness are extremely sparse.

Specifically, the ground water in the unconsolidated outwash and alluvial aquifers in much of the Ohio River valley, and in the Wabash, Miami, lower Scioto, and Allegheny subbasins can be considered a regional resource. In these areas ground water can satisfy more than local needs.

For example, the water requirements for a large population increase in the above areas can be satisfied with ground water. In order to estimate the actual population that can be satisfied, the following assumptions were made:

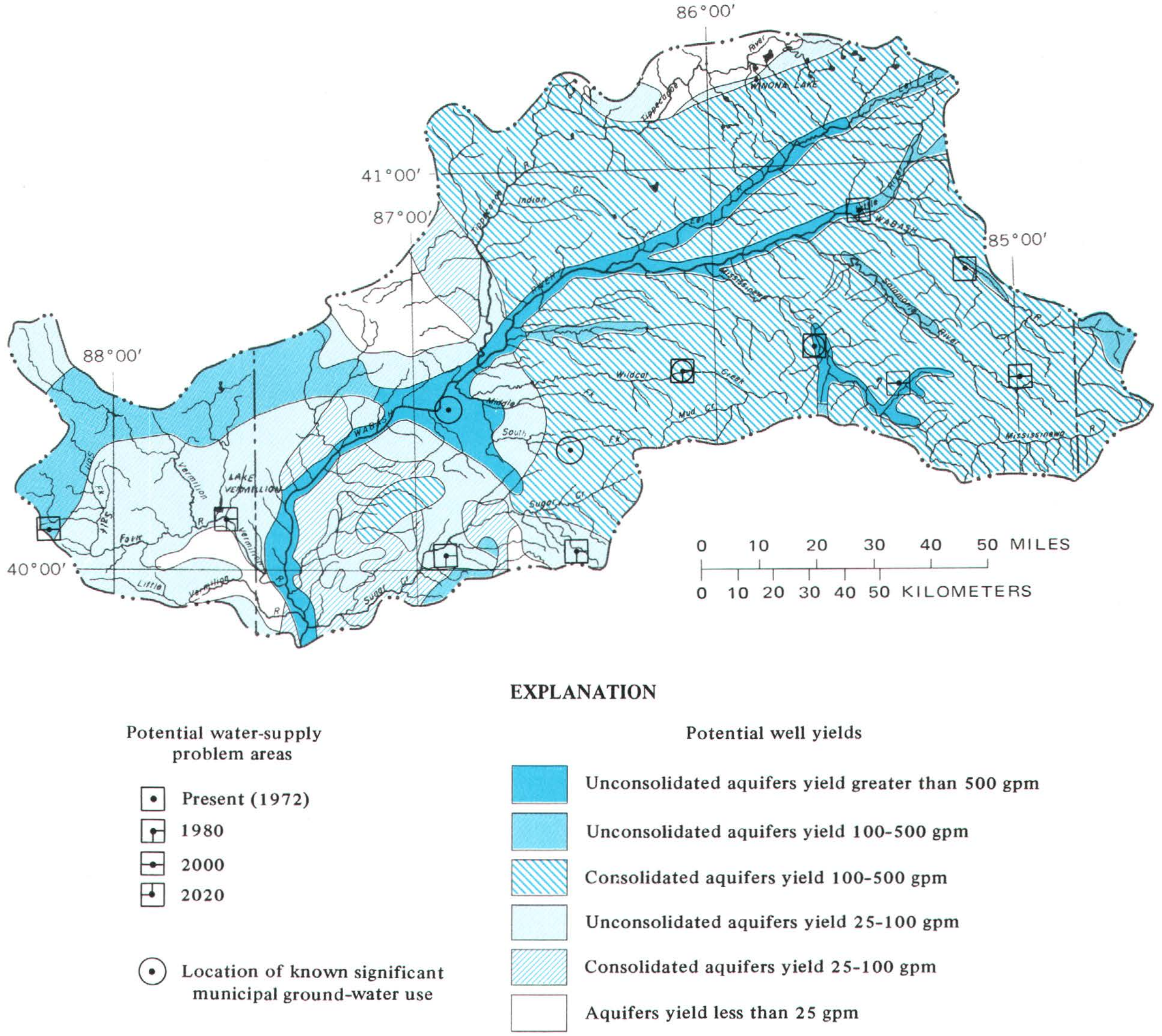


FIGURE 14. — Potential water-supply problem areas, potential well yields, and present ground-water use in the upper Wabash River drainage.

1. One-half the excess of annual ground-water recharge over base-year (1960) ground-water use is available. This should be a conservative estimate of available water.
2. All base-year industrial water use is from ground-water sources. This also causes the estimate of available water to be conservative.
3. The available water is used only once. Again, this causes the estimate of available water to be conservative.
4. Per-capita water use is 150 gpd (gallons per day). Therefore, a 1-mgd supply will satisfy the requirements of approximately 6,500 people.

On the basis of the above assumptions, ground water is available for 22 million additional people in the Wabash subbasin, and for 4, 1.5, and 12 million additional people, respectively, in the Miami, lower Scioto, and Allegheny subbasins.

The above estimates are given for illustration only. Instead of supporting a population increase, the available ground water in these subbasins could be utilized for industrial or agricultural expansion or for other uses. However, factors other than water supply constrain and determine development potential.

Ground water also is available in the Ohio River valley for approximately 5 million additional people. This estimate is based on the previously stated assumptions, except that a different method was used to estimate ground-water recharge. Because the Ohio River is regulated, streamflow data could not be used to estimate ground-water recharge. Instead, Rorabaugh's (1949) estimates of recharge were used.

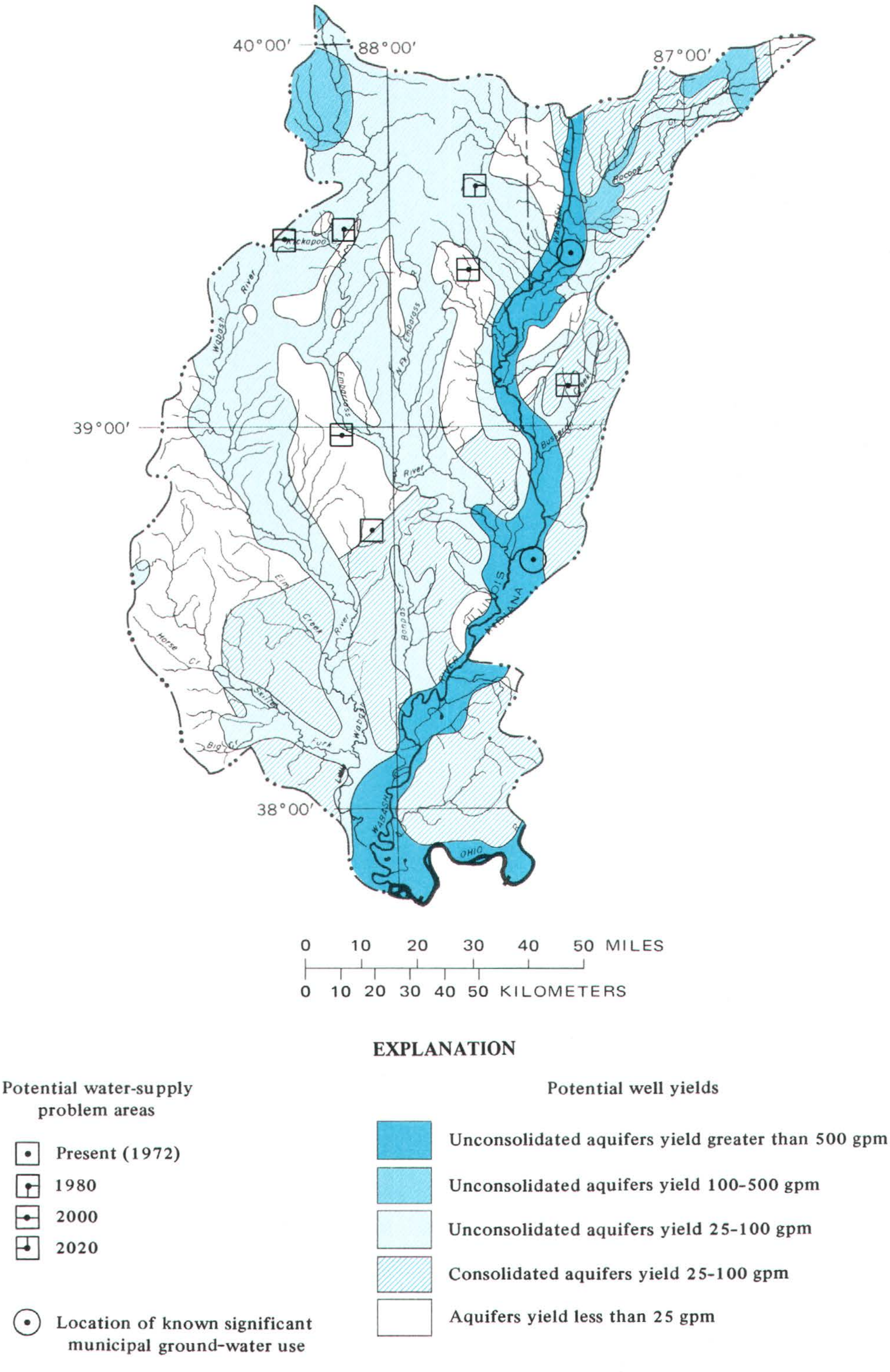


FIGURE 15. — Potential water-supply problem areas, potential well yields, and present ground-water use in the lower Wabash River drainage.

Natural recharge to the outwash and alluvium in the Ohio River flood plain is partly by flow through the permeable rocks of the uplands adjacent to the outwash and alluvium and partly by direct downward seepage of precipitation.

For the purposes of this report, where a conservative estimate of recharge and available ground water is desired, zero recharge is assumed from the uplands. Sparse data on such recharge also make such an assumption necessary.

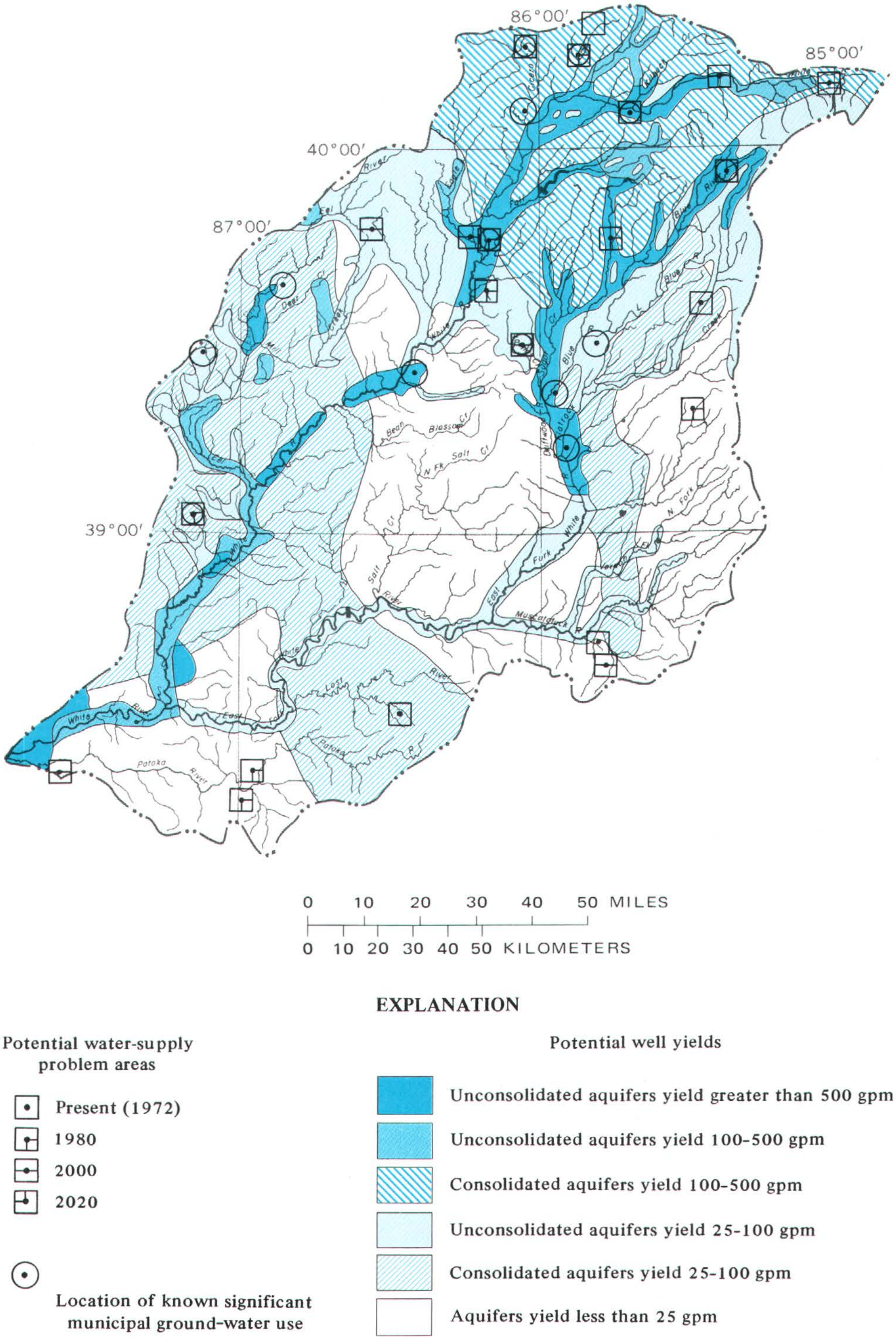
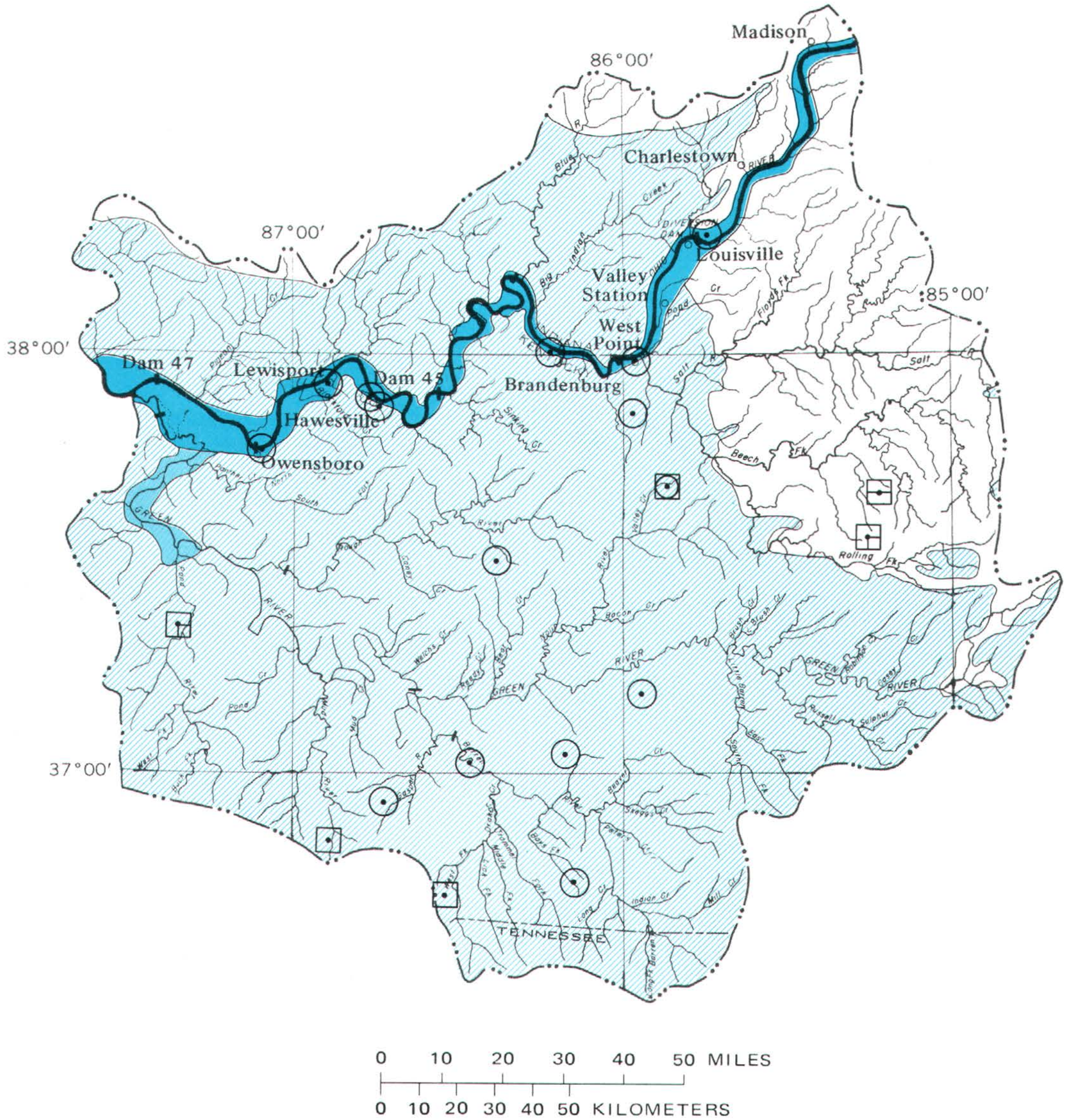


FIGURE 16. — Potential water-supply problem areas, potential well yields, and present ground-water use in the White River drainage.

Assumed recharge per square mile of outwash and alluvium from seepage of precipitation is 200,000 gpd. Rorabaugh (1949, p. 21) estimated seepage to the aquifer southwest of Louisville, Ky., in 1945 of about 250,000 gpd per square mile. However, because 1945 was a wet year, seepage would be less in dry years. Therefore, an average seepage of 200,000 gpd per square mile is assumed. The author also assumes that this estimate is applicable to the outwash and alluvium along the entire length of the Ohio River.



EXPLANATION

Potential water-supply problem areas

- Present (1972)
- 1980
- 2000
- 2020

Location of known significant municipal ground-water use

Potential well yields

- Unconsolidated aquifers yeild greater than 500 gpm
- Unconsolidated aquifers yield 100-500 gpm
- Consolidated aquifers yield 25-100 gpm
- Aquifers yield less than 25 gpm

FIGURE 17. — Potential water-supply problem areas, potential well yields, and present ground-water use in the Green–Salt–Lower Ohio River subbasin.

Recharge from seepage of precipitation into the entire aquifer(s) in the Ohio River valley is about 2,000 mgd. This is the product of 10,000 square miles, or approximate aquifer area (table 3), and 200,000 gpd per square mile, or assumed recharge rate.

Finally, using the above estimate of recharge and

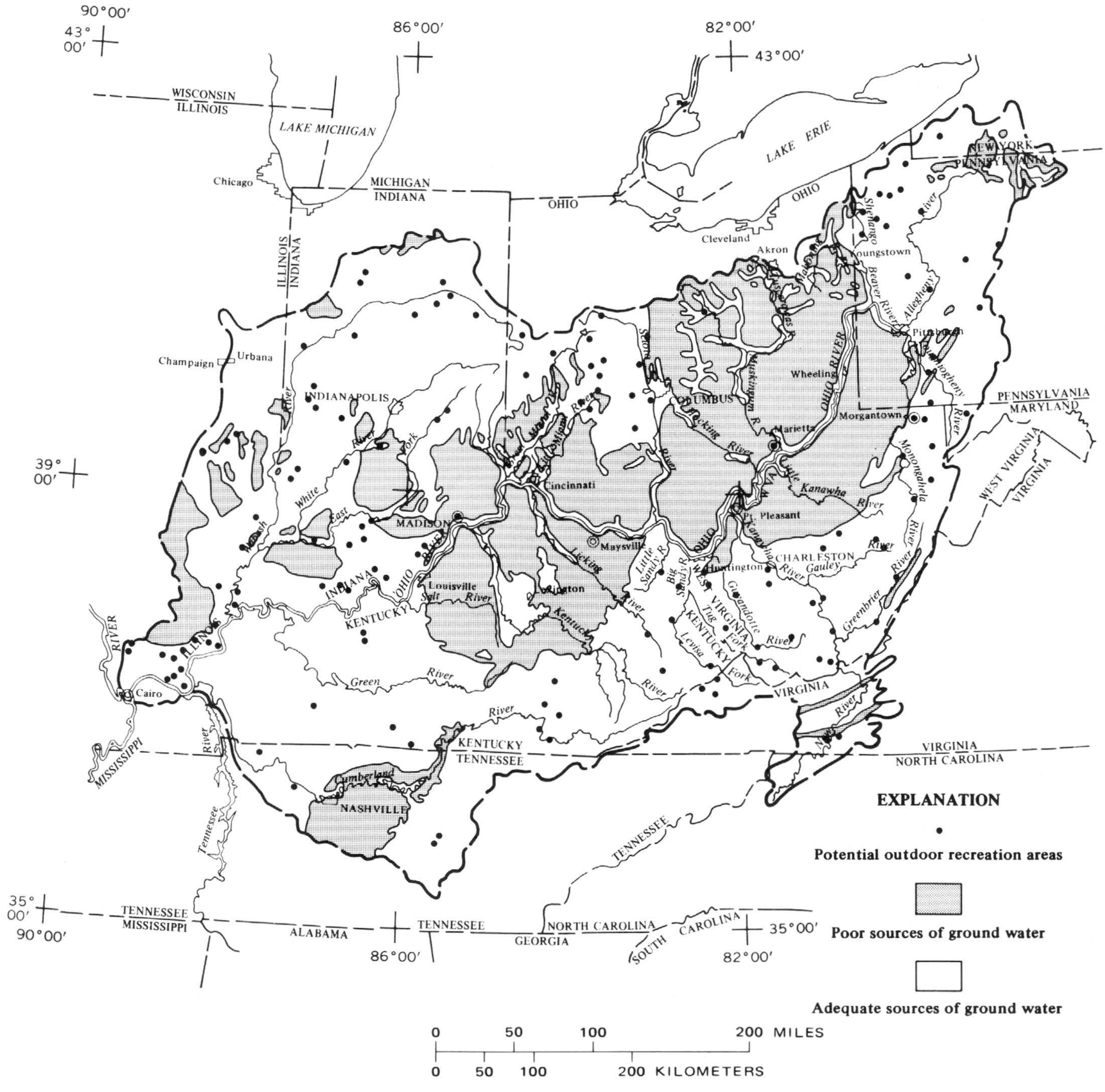


FIGURE 18. — Ground-water supply and potential outdoor recreation areas.

base-year water use (table 7), ground water is available in the Ohio River valley for approximately 5 million additional people.

In summary, ground water is available for 22 million additional people in the Wabash subbasin; for 4, 1.5, and 12 million additional people, respectively, in the Miami, lower Scioto, and Allegheny subbasins; and for 5 million additional people in the Ohio River valley.

Even though the above figures are gross, the obvious fact is that ground water is available in significant amounts in at least 5 percent of the region.

Of further importance to the planner, a reasonable assumption is that much of the available ground water in the above areas can be pumped and transported to relatively distant points of need. For example, approximately 55,000 people in the Fort Knox, Ky., area, southwest of Louisville, are served with ground water delivered from approximately 10 miles away (Mull and others, 1971). Several other communities in Kentucky also pump ground water from the outwash and alluvial aquifer in the Ohio River valley and transport the water to relatively distant points of use.

To make maximum use of the available ground-water resources of the region, the population-density pattern should be one of maximum population density adjacent to the Ohio River, and in the Wabash, Miami, lower Scioto, and possibly the Allegheny subbasins. An illustration, comparing ground-water supply, population density, and the interstate highway system (fig. 19), suggests that all areas of existing high population density have the potential for development of ground-water resources. The Indianapolis, Ind., area probably has the highest potential for ground-water development. Among the major population areas, the Youngstown, Ohio, area and the Nashville, Tenn., area probably have the poorest potential for ground-water development.

Assuming that future population growth will be heaviest in the areas paralleling the insterstate highway system, much of the increased water demand associated with these growth areas can be supplied by ground water. The areas of potential growth in Indiana and southwestern and south-central Ohio are especially well situated in terms of potential ground-water supplies. The development of the ground-water resources in western Pennsylvania and West Virginia probably depends primarily upon water-quality considerations, rather than upon availability of the resource.

The potential for additional industrial development also is enhanced in the areas where ground water is classified as a regional resource. Almost any type of industry can satisfy its water requirements with ground water in these areas.

THE POTENTIAL FOR UNDERGROUND WASTE DISPOSAL

Underground space in the Ohio Region also can be considered a regional resource in the sense that it can be included in regional water-pollution-control or waste-disposal plans. As previously suggested, a simple definition of natural underground space might be interconnected pore or fracture space into which a fluid can be emplaced. In this section of the report emphasis is upon underground space occupied by saline ground water. Before assessing the potential for underground waste storage in the region, a discussion is presented on the characteristics generally considered to be necessary for successful waste injection and underground storage.

Two geologic characteristics generally considered necessary for the use of waste-injection wells are (1) an injection zone with sufficient permeability, porosity, thickness, and areal extent to serve as a liquid-storage reservoir at safe injection pressures, and (2) an injection zone that is below the level of fresh-water circulation and is confined above by rocks that are, for practical purposes, impermeable to waste liquids.

Metamorphic and igneous crystalline rocks, which everywhere underlie the sedimentary rocks of the region, provide little potential for underground liquid-waste disposal because of lack of storage space and low permeability. Artificial tunnels or chambers in these rocks may facilitate storage under certain conditions. Warner (1969, p. B-28-A) listed characteristics of areas feasible for waste injection and underground storage.

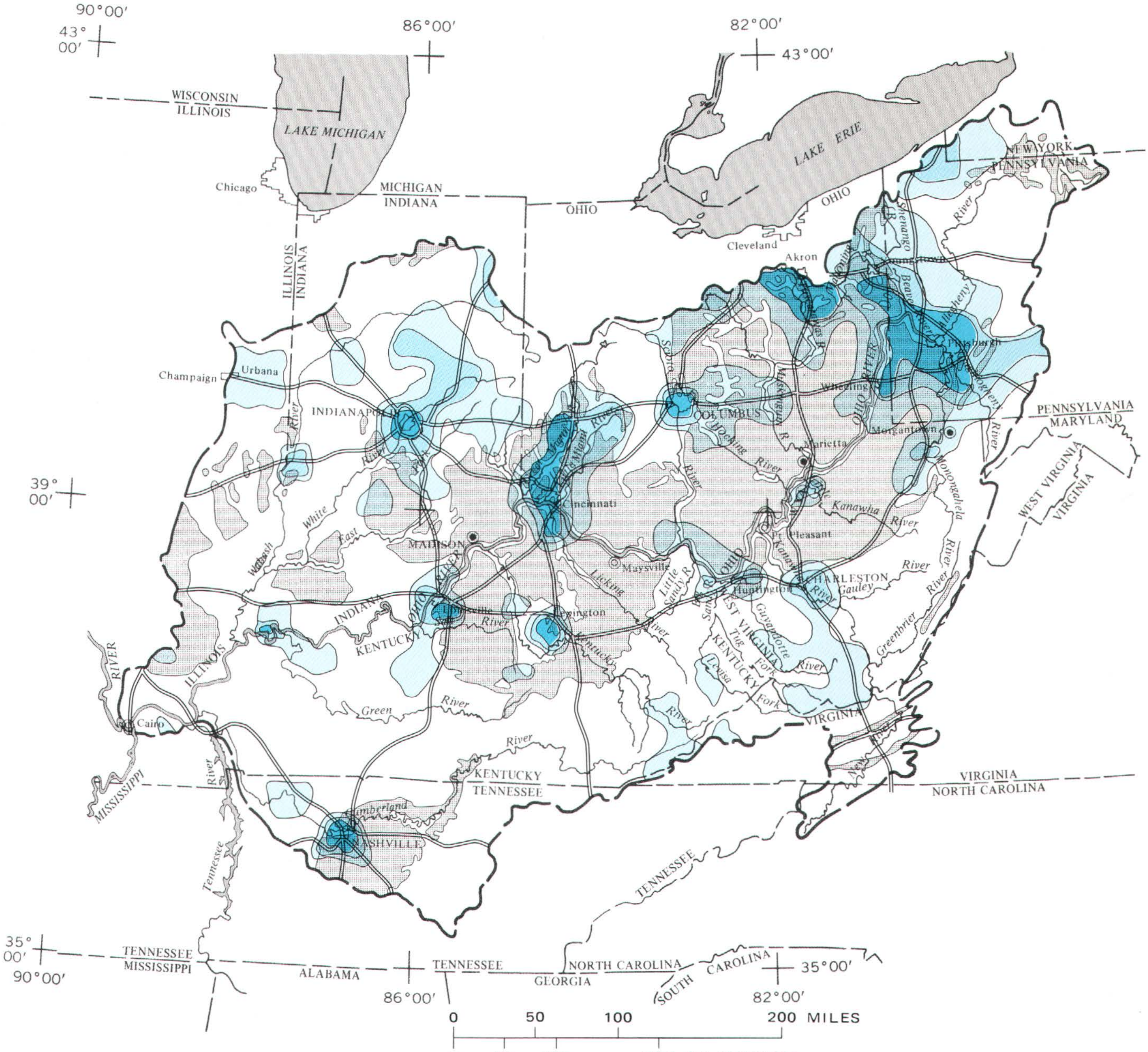
On the basis of considering these characteristics, known conditions in the Ohio Region warrant investigation of waste-disposal potential in practically the entire region. In much of southern Illinois, southwestern Indiana, West Virginia, southwestern Pennsylvania, and extreme southeastern Ohio there is at least 1,500 to 2,000 feet of Mississippian and Pennsylvanian sedimentary rock present at considerable depth; in northwestern Pennsylvania, eastern Ohio, and south-central Indiana there are comparable thicknesses of Silurian and Devonian rock (Warner, 1969, fig. 9).

Although there is a great potential for underground waste storage in the Ohio Region, storing wastes underground is not a pollution panacea. The properties of the potential host rock and adjacent formations must be thoroughly understood. Waste injection undertaken without a knowledge of the limitations of the host formation may lead to undesirable or disastrous consequences. Possible consequences are the escape of waste to the surface or near-surface environment; the contamination of soils, surface water, ground water and other resources; and the denial of the use of other resources, such as oil and mineral ores. Evidently, effective underground waste management requires development of new technology (R. L. Nace, written commun., 1972).

Further discussion of waste management is beyond the scope of this report. However, the technical aspects of the use of salaquifers for waste storage is now under study by the U.S. Geological Survey.

PLANNING FOR GROUND-WATER UTILIZATION — AN EXAMPLE OF SIMULATION TECHNIQUES FOR GROUND-WATER SYSTEMS

The purpose of this section of the report is to demonstrate the relevancy of ground-water simulation techniques in solving a water-supply problem. As an example, a digital model of a small part of the stream-aquifer system south of Columbus, Ohio, was developed. S. E. Norris and other personnel of the U.S. Geological Survey office in Ohio contributed basic data and geohydrologic information that made development of the model possible. The model was developed in a very short time, for illustrative purposes. No verification of the



EXPLANATION

- Adequate sources of ground water
- Poor sources of ground water
- More than 400 people per square mile
- 200-400 people per square mile
- 100-200 people per square mile
- Interstate highway route

FIGURE 19. — Ground-water supply, population density, and interstate highway system.

model was attempted. In the study of an actual model the hydrologist generally verifies the model by simulating historical ground-water level changes caused by pumping, on the assumption that if the model simulates historical conditions it will also closely predict future conditions. The intent of the example is to demonstrate the methodology rather than to develop a verified model. Data related to the degree of stream-aquifer connection and data on hydraulic head differences between the stream and aquifer are scant. Such data are critical in determining actual drawdowns in the aquifer. Therefore, the model results should be considered as hypothetical.

The Columbus, Ohio, area was chosen for the example because large amounts of ground water are available in the aquifer system under the area and because the potential for additional surface storage in relation to need is small. Therefore, the Columbus area seemed a logical one in which to consider feasibility of conjunctive use of surface-water and ground-water resources.

A rather typical approach to solving a water-supply problem is used in the example. The surface-water supply is evaluated both in terms of average conditions and in terms of the critical period; the demand for water is compared with the surface-water supply; and, then, the ground-water supply is evaluated. Note, however, that the ground-water supply is evaluated for only a small part of the total Columbus area.

WATER RESOURCES VERSUS WATER DEMANDS IN THE COLUMBUS AREA

The major developed water resources of the Columbus area are the Scioto and Olentangy Rivers and Alum and Big Walnut Creeks. The city of Columbus has three surface reservoirs to store streamflow: O'Shaughnessy and Griggs Reservoirs on the Scioto River, with capacities of 5,520 and 1,440 million gallons, respectively, and Hoover Reservoir on Big Walnut Creek with a capacity of 19,660 million gallons. Because sediment-inflow estimates were not readily available, the above storage volumes for the surface reservoirs are assumed to be constant with time.

Streamflow records were used to estimate average monthly surface inflows to the three reservoirs operated by the city of Columbus (table 11). Streamflow records for the Scioto River near Prospect, Mill Creek near Bellepoint, and Big Walnut Creek at Central College were used in computing the monthly inflows. The amount of inflow to O'Shaugnessy Reservoir derived from an ungaged area of 235 square miles above the reservoir was estimated using the formula:

Ungaged inflow = 0.166 Prospect + 0.790 Bellepoint. In the above formula, Prospect refers to the Scioto River flow near Prospect and Bellepoint refers to the Mill Creek flow near Bellepoint. The formula is based on a simple areal relation. The first coefficient in the formula is the product of Prospect flow per unit drainage area and 40 percent of the ungaged drainage area. The second coefficient is the product of Bellepoint flow per unit drainage area and 60 percent of the ungaged drainage area. In other words, the assumption was made that 40 percent of the ungaged area had the same streamflow per unit drainage area as the Scioto drainage above Prospect and that 60 percent of the ungaged area had the same streamflow per unit of drainage area as the Mill Creek drainage. Much more accurate estimates of inflow to O'Shaughnessy and Griggs Reservoirs would be possible

TABLE 11. — *Estimated average monthly inflow to O'Shaughnessy, Griggs, and Hoover Reservoirs*

Month	Flow (mgd)			Estimated ungaged flow (mgd)	Estimated total inflow[1] (mgd)
	Scioto River near Prospect	Mill Creek near Bellepoint	Big Walnut Creek at Central College		
October	115	11	15	19+ 12= 31	170
November	180	72	56	30+ 44= 74	380
December	377	194	118	63+ 93=156	850
January	791	362	288	131+228=359	1,800
February	746	378	291	124+230=354	1,770
March	1,016	400	363	169+287=456	2,240
April	859	326	285	143+225=368	1,840
May	422	161	149	70+118=188	920
June	364	202	130	60+103=163	860
July	178	95	35	30+ 28= 58	370
August	109	42	31	18+ 25= 43	230
September	106	17	18	18+ 14= 32	170

[1]Inflow values have been rounded off.

TABLE 12. — *Estimated critical-period inflow to O'Shaughnessy, Griggs, and Hoover Reservoirs*

Month	Flow (mgd)			Estimated ungaged flow (mgd)	Estimated total inflow (mgd)
	Scioto River near Prospect	Mill Creek near Bellepoint	Big Walnut Creek at Central College		
May	157	59	45	73	[1]330
June	85	63	35	64	[1]250
July	13	1	1	3	18
August	10	2	0	3	15
September	7	1	1	2	11
October	7	1	2	2	12
November	10	2	1	3	16
December	11	3	3	4	21
January	10	4	5	4	23
February	286	243	333	239	[1]1,100

[1]Inflow value has been rounded off.

if a stream gage were present on the Scioto River just above O'Shaughnessy Reservoir.

The estimated average yearly inflow to the three reservoirs, based on the above estimates of monthly inflows, is approximately 3.5×10^5 million gallons, or about 960 mgd.

Again using streamflow records and the above formula for estimating inflow from the ungaged drainage area, monthly values for critical-period inflow were estimated for the three surface reservoirs (table 12). The critical period of record for the Scioto River near Prospect is assumed as May 1944 to February 1945. This critical period is assumed to be applicable to the other records under consideration in this example.

Another major water resource in the Columbus area is the ground water available from storage in the unconsolidated glacial and alluvial deposits. Lesser volumes of water are available from the consolidated aquifers in much of the Scioto basin above Columbus, but this potential supply is not considered in this example. A 50-foot-thick layer of aquifer in an area of 70 square miles, just south of Columbus, is considered (fig. 20). Outwash deposits are present in about 19 square miles of the 70-square-mile area; till is present in the rest of the area. The use of the renewable ground-water resource from storage here is not new to the city of Columbus. During the severe drought of the early 1960's, the city planned and developed a well field to tap the outwash and alluvial aquifer adjacent to Alum Creek.

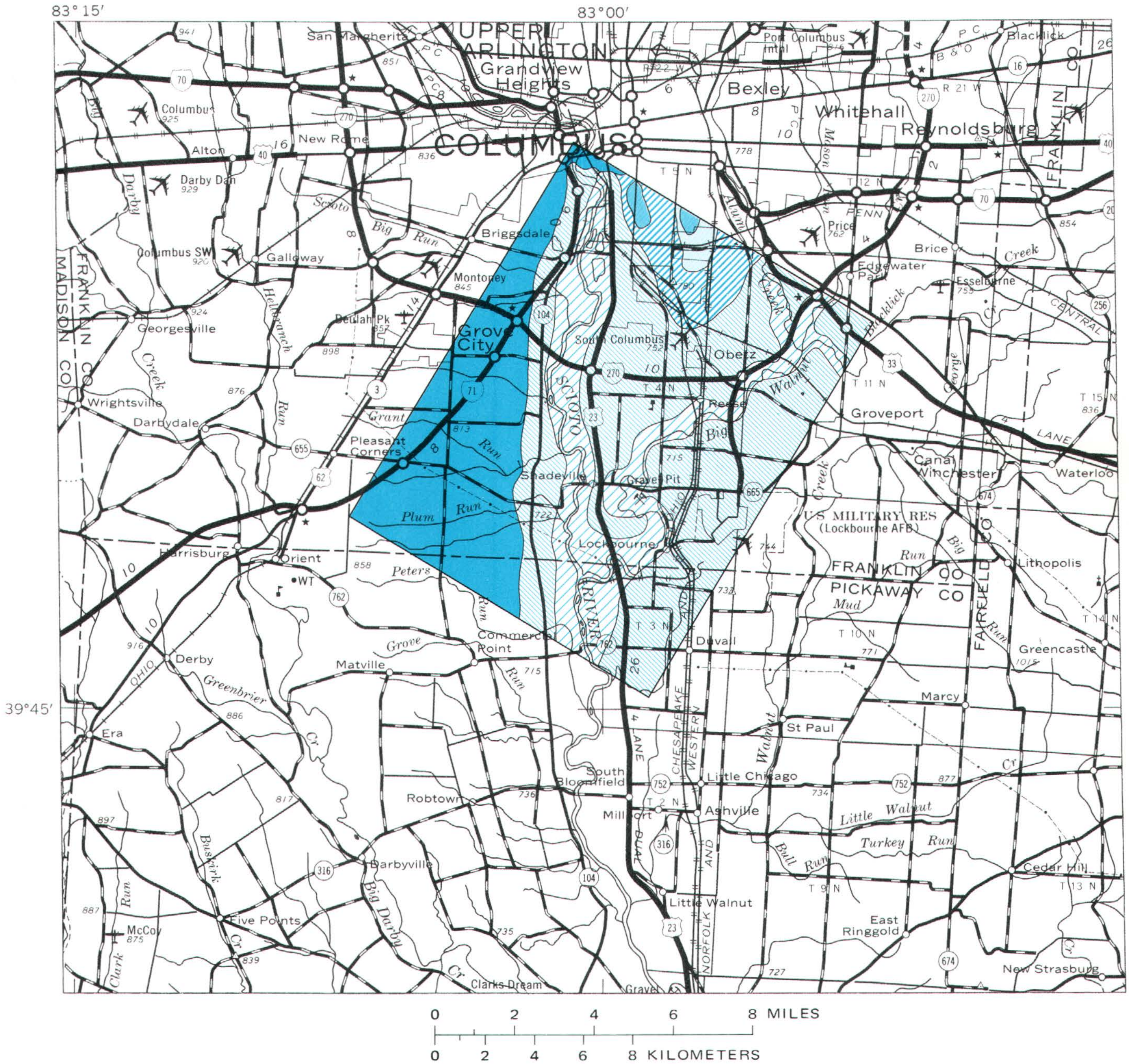
The average water demand for Columbus in the year 2000 is estimated to be 350 mgd (Ohio Division of Water, 1963, pl. 16), or almost 130,000 million gallons per year. Because demand is not constant throughout the year, average demand for each month was estimated. Monthly demand is assumed at a relative maximum during June, July, and August; demand is assumed at a relative minimum from November through February (table 13).

Even though the period of maximum water demand

TABLE 13. — *Comparison of estimated critical period inflow with estimated daily and monthly water demand for the year 2000*

Month	Percent of yearly water demand	Monthly water demand[1] (million gallons)	Daily water demand (mgd)	Surface-water supply (mgd)	Daily water deficit (mgd)	Monthly water deficit[1] (million gallons)
May	9	11,500	371	330	41	1,270
June	10	12,780	426	250	176	5,280
July	10	12,770	412	18	394	12,210
August	10	12,770	412	15	397	12,310
September	9	11,130	371	11	360	10,800
October	8	10,230	330	12	318	9,860
November	7	9,240	298	16	282	8,460
December	7	8,930	288	21	267	8,280
January	7	8,930	288	23	265	8,220
February	7	9,250	319	1,100	----	----
Total deficit	--	----	----	----	----	76,690

[1]Values have been rounded.



EXPLANATION

Transmissivity values, in gallons per day per foot, and storage coefficient

- T = 80,000 and S = 0.20
- T = 40,000 and S = 0.01
- T = 20,000 and S = 0.01
- T = 4,000 and S = 0.01
- T = 400 and S = 0.01
- T = 0

—— Model boundary

FIGURE 20. — **Area of model and assumed values for transmissivity and storage coefficient.**

does not coincide with the period of maximum surface-water supply, the available surface-water reservoirs have sufficient carryover storage volume to satisfy demands if average or greater than average streamflow occurs.

During the critical period, the carryover storage volume in the existing surface reservoirs is not sufficient to satisfy the estimated water demand in the year 2000. After considering dead-storage requirements, the total available surface-reservoir storage is 26,640 million gallons. During the critical period of 9 months there is a water deficit of about 77,000 million gallons, in terms of surface-water inflow versus demand (table 13). Even assuming considerable error in the above monthly breakdown in demand, there is a deficit in terms of critical-period surface-water supply and demand. Therefore, additional surface storage must be made available or the ground-water resource must be utilized.

Once a demand for ground water is evident, as in the example above, a hydrologic model can be used to evaluate the capability of an aquifer or aquifers to satisfy all or part of that demand.

The data input to the model is as follows:

1. Transmissivity: 40,000 to 80,000 gallons per day per foot (fig. 20).
2. Storage coefficient: 0.01 and 0.20.
3. Aquifer thickness: 50 feet.
4. Hydraulic conductivity of stream bottoms: 27 gallons per day per square foot.
5. Thickness of streambed: 5 feet.
6. Width of Sciotto River and Big Walnut Creek: 100 feet.
7. Nodal spacing: 1,056 feet.

USE OF A HYDROLOGIC MODEL TO EVALUATE AQUIFER CAPABILITY

A detailed theoretical development of the digital model utilized is given in a report by Pinder and Bredehoeft (1968), and is not repeated in this report. They also discuss the assumptions necessary in using the model. The digital model is designed to solve the equations of flow for the complex hydrologic systems encountered in nature, and is based upon finite-difference approximations to the flow equations. Solutions to the flow equations are calculated for each nodal point of an established finite-difference network. In the example model of the Columbus area, the established network is a rectangular 55-row by 45-column matrix with a total of 55x45 or 2,475 nodal points. The nodal points are equally spaced on ⅕-mile centers. Each of the nodel points is a point of data input and output.

The model was used to simulate the response of the aquifer system in the Columbus area to a hypothetical pumping stress during a 9-month critical period, with a 10-foot ground-water-level drawdown limitation. The 10-foot decline is 20 percent of the assumed aquifer thickness. Such a limitation or set of conditions must be stated prior to determining "available" water. Available water is the amount of ground water that can be withdrawn on some sort of an areal basis, and for a very long period of time, under the conditions stated.

Continuous pumpage of 22 mgd for 9 months was simulated. Each of 22 simulated wells located along lines parallel to the Scioto River and Big Walnut Creek was pumped at a rate of 1 mgd. The simulated wells were located approximately on 1-mile centers (fig. 21). By placing the wells adjacent to the stream channels, recharge is induced from the streams, and, therefore, not all the water pumped from the wells is from ground-water storage. Actually, about 80 percent of the water pumped is induced recharge from the two streams. In actual development the well-field configuration can be determined in such a way that some other percentage of the water pumped is river water induced to flow to the wells.

The output of the model — the computed ground-water-level decline values for each nodal point (fig. 22) — suggests that the modeled stream-aquifer system can supply 22 mgd under the conditions stated. Actually, much more water is available because nowhere in the modeled area is there a computed decline in excess of 7 feet after 9 months of pumping (fig. 22). However, the available water should not be overestimated from the small drawdowns indicated by the model. The drawdown, or head, calculated by the model at a node where pumping is simulated, should be related to a well with a diameter of about 440 feet. Using a formula derived by Prickett and Lonnquist (1971, p. 61), the drawdown in a 24-inch-diameter simulated well would be about 5.5 feet greater than was indicated by the model. In study of an actual model, more precise water-availability values could be estimated by designing an optimal well-field pattern. Again, however, the purpose of this example is simply to demonstrate the methodology.

SUMMARY

Ground water in the Ohio Region is a large, important, and manageable resource that should have a significant role in regional water development.

Total potable ground water available from storage in the outwash and alluvial aquifers in the Ohio River valley and the subbasins is about 23,000 billion gallons. This is about four times the flood-control storage of all Ohio region Corps of Engineers reservoirs constructed, under construction, or in advance planning as of July 1965.

Approximately 85,000 billion gallons of potable ground water is available from storage in the region in aquifers other than the outwash and alluvial aquifers.

Base from U.S. Geological Survey, 1967

0 2 4 6 8 MILES

0 2 4 6 8 KILOMETERS

EXPLANATION

o
Simulated well

Model boundary

FIGURE 21. — Map showing placement of simulated pumping wells.

This is about 20 percent of estimated storage in Lake Ontario.

Estimated average annual ground-water recharge in the subbasins is about 35,000 mgd; estimated recharge from seepage of precipitation into the aquifer(s) in the Ohio River valley is about 2,000 mgd.

About 5 percent of the region has ground-water resources capable of satisfying more than local needs. For example, under certain specified conditions the excess of ground-water recharge over base-year (1960) ground-water use is available for 22 million additional people in the Wabash subbasin; for 4, 1.5, and 12 million

FIGURE 22. — Computed ground-water-level decline after pumping simulated wells for 9 months.

additional people, respectively, in the Miami, lower Scioto, and Allegheny subbasins; for 5 million additional people in the Ohio River valley; or for equivalent magnitudes of water supply for industry, agriculture, or other uses. A reasonable assumption is that much of the available ground water in these areas can be pumped and transported to reasonably distant points of need. However, factors other than water supply constrain and determine development potential.

Rapid advance of techniques in ground-water hydrology during recent years has provided methods which the hydrologist and planner can use for evaluating planned ground-water development in high potential areas such as those mentioned above. As an example of simulation techniques, a digital model of a small part of the stream-aquifer system south of Columbus, Ohio, was developed. Although the model results should be considered hypothetical because no model verification was attempted, the output of the model illustrates the technical feasibility of conjunctive development of a local ground-water surface-water system.

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