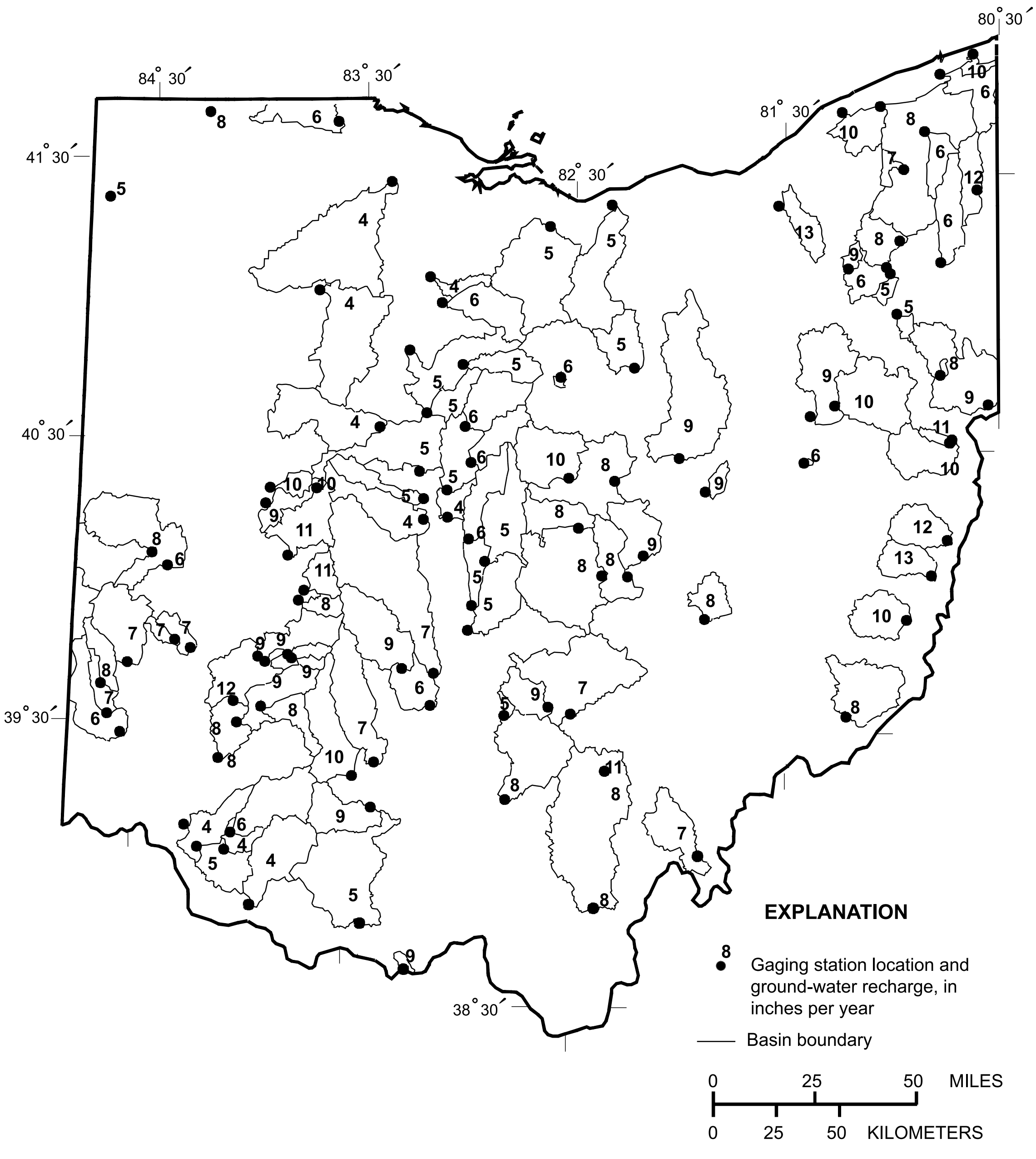
Use of Streamflow Records and Basin Characteristics to Estimate Ground-Water Recharge Rates in Ohio



Ohio Department of Natural Resources
Division of Water

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch	2.54	centimeter
foot (ft)	0.3048	meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Use of Streamflow Records and Basin Characteristics to Estimate Ground-Water Recharge Rates in Ohio

By Denise H. Dumouchelle and Michael C. Schiefer

Abstract

Ground-water recharge rates were estimated for 103 basins in Ohio by use of the computer programs RECESS, RORA, and PART to analyze long-term daily streamflow records. Estimates of ground-water recharge, discharge, and mean base-flow index (MBI, a ratio of mean base flow to mean streamflow) are reported for these basins. Selected basin characteristics were examined qualitatively to identify possible relations between characteristics and the estimated ground-water recharge rates. Characteristics were determined by use of statewide data and a Geographic Information System (GIS).

Several general characteristic-recharge relations indicate that precipitation rates, soil-infiltration rates, and glacial geology can be used to estimate a range of recharge rates for a basin. For example, basins with 20 percent or more coverage of soils with very low infiltration rates tended to have recharge rates of less than 6 in/yr (inches per year), whereas basins with 20 percent or more coverage of soils of high infiltration rates tended to have recharge rates of 8 in/yr or more.

For estimation of recharge rates in basins without long-term daily streamflow records, several methods were tried using the relations found with the recharge-discharge estimates, MBI, basin characteristics, and low-flow statistics. Recharge estimates for 30 basins with only a few years of daily streamflow records were made by means of results from the PART program, plus basin characteristics. Estimates for 28 basins where only partial low-flow records were available were made by means of basin characteristics and a relation between the 90-percent-duration flow and the MBI.

If no streamflow records are available for a basin, a range of ground-water recharge rates can be estimated on the basis of qualitative basin characteristics. For basins with even just a few years of streamflow data, ground-water recharge can be estimated from the computer programs RECESS, RORA, and PART. Ground-water recharge estimates for Ohio, based on the streamflow data for 161 basins, range from 3 to 16 in/yr, with a median of 6 in/yr.

Introduction

The hydrologic cycle is a building block for hydrogeologic studies. The basic cycle is precipitation entering either surface water or ground water and water returning to the atmosphere through evaporation. Many hydrologic studies concern the interaction among the various components of the hydrologic cycle. For example, surface water may recharge the ground-water system or ground water may discharge to surface-water bodies. These important interactions of the hydrologic cycle can be critical in understanding water budgets and in managing stream basins.

One of the most difficult components of the hydrologic cycle to estimate is the rate at which precipitation reaches (recharges) the ground-water system. The amount of precipitation that an area receives determines an upper limit on the amount of water that can recharge the ground-water system by natural means; however, because many factors affect the rate of recharge, the amount of recharge cannot be reasonably defined as a simple fixed percentage of precipitation.

In the surface-water system, the component of flow that consists of ground water that discharges into the stream is called base flow (Fetter, 1988). In many studies, base flows and ground-water recharge rates have been estimated by means of physical, chemical, and isotopic techniques. These include streamflow-hydrograph separation, ground-water-flow models, ground-water-budget studies, ground-water-level fluctuations, geochemical tracers, tritium isotopes, and derivation of empirical relations (Pettyjohn and Henning, 1979; Holtschlag, 1997). Hydrograph-separation methods are used widely to estimate base flow from streamflow records. As an alternative to hydrograph separation, recession-curve displacement (or the Rorabaugh method), can be used to estimate ground-water recharge from streamflow records.

Although some problems are associated with the assumptions behind the method, effective ground-water recharge rates can be estimated by the use of computerized analysis of streamflow records. In 1999, the U.S. Geological Survey (USGS) and the Ohio Department of Natural Resources, Division of Water (ODNR) began a comprehensive, statewide project to determine ground-water-recharge estimates based on streamflow records. This work was supported in part through a grant from the Ohio Environmental Protection Agency under provisions of Section 319 of the Clean Water Act, as amended in 1987.

Purpose and scope

The purpose of this report is to present statewide estimates of ground-water recharge rates for Ohio. The recharge estimates are based on computerized analysis of long-term streamflow records from 103 streamflow-gaging stations. These recharge estimates were compared to selected basin characteristics, and the resulting correlations were used to estimate recharge rates in 58 basins with less than 10 years of streamflow record.

Description of study area

Ohio lies within the Great Lakes and Ohio River drainage basins. The temperate climate consists of hot, humid summers and fairly cold winters. The average annual precipitation ranges from less than 30 in. to more than 43 in., with substantial local variation across the state. The highest precipitation generally is in the northeastern and the southwestern parts of the State, and the lowest is in the north to northwestern parts (Harstine, 1991).

Glacial deposits cover about two-thirds of Ohio, mostly in the northern, and, western parts of the State. The glacial deposits are mainly clayey till interspersed with sand and gravel layers and appreciable deposits of outwash sands and gravels in major valleys. Extensive deposits of glacial outwash form major aquifers in several areas, notably along the Mad, Great Miami, Scioto, Hocking, Tuscarawas, and Muskingum Rivers. In glaciated areas the topographic relief is generally low. Glacial deposits are absent in southeastern Ohio, where bedrock is usually at or near land surface. The bedrock in this area consists of relatively thin alternating layers of sandstone, shale, coal and limestone. Relief ranges from nearly flat grasslands to steep, timber-covered hills (Pettyjohn and Henning, 1979).

Previous investigations

Many investigators have worked on the problem of estimating ground-water recharge and discharge from streamflow records. (See reference list in Rutledge, 1998.) Methods used to analyze streamflow records in this manner are sometimes collectively called hydrograph-separation techniques.

Hydrograph-separation techniques are widely used to estimate ground-water discharge from streamflow records. These techniques are used to separate the streamflow hydrograph into distinct components attributed to surface-water runoff and ground-water discharge. Pettyjohn and Henning (1979) developed and applied a computer program to estimate ground-water discharge from selected wet, dry, and normal years in Ohio. Koltun (1995) used the HYSEP program to partition streamflow records for the Mad River in Ohio in order to estimate long-term mean annual base flows. Holtschlag (1997) used the PART program to partition streamflow records from the Lower Peninsula of Michigan in order to relate the ground-water discharge to basin characteristics through regression analysis.

Recession-curve displacement, also known as the Rorabaugh method (Rorabaugh, 1964), is an alternative to partitioning of streamflow records that gives estimates of ground-water recharge rates. Hoos (1990) manually applied the Rorabaugh method to streamflow records in Tennessee to obtain recharge estimates for various hydrogeologic settings. Rutledge (1998) developed RORA, an automated application of the Rorabaugh method. Testing of RORA against the manual Rorabaugh method for numerous streamflow records in the eastern United States showed close correlation of results (Rutledge and Daniel, 1994). Halford and Mayer (2000) suggest that hydrograph-separation techniques are poor tools for estimating ground-water discharge and recharge when the major assumptions are violated and that multiple methods of estimating ground-water recharge should be used because of the uncertainties in any one method.

Methods

In this study, ground-water recharge rates were estimated from long-term streamflow records by use of computer programs. Streamflow data used in this study were selected to meet the application criteria of the programs used to estimate ground-water recharge. Two sets of stations were analyzed by means of these programs, and a third set of stations with only low-flow partial records was analyzed as a test for estimating ground-water recharge rates for basins with no continuous daily long-term streamflow records. Characteristics such as geology and soil infiltration were determined for each basin using a geographic information system (GIS).

Computer programs for analysis of streamflow records

Streamflow records were analyzed by the use of three related computer programs: RECESS, RORA, and PART. The following discussion of these programs is from the report describing the programs (Rutledge, 1998) and from conversations in 1999 and 2000 with the author of the programs, Albert T. Rutledge. Proper application of these programs requires the following:

- diffuse and areal recharge
- except for riparian evapotranspiration, ground-water discharge entirely to the stream
- a streamflow-gaging station at the sole stream outflow for the basin
- negligible streamflow regulation or diversion
- drainage areas between 1 and 500 mi^2
- sufficient periods of streamflow record
  for RECESS, at least 10 years of continuous record
  for RORA and PART, continuous record for the period of interest

The results of these programs may not be reliable for basins dominated by interaction with regional ground-water-flow systems, snowmelt runoff, recharge from losing streams, ground-water withdrawals, or prolonged periods of surface runoff. RECESS is an interactive program, whereas RORA and PART largely are automated.

RECESS was used to obtain the median recession index, which is the time required for ground-water discharge to recede by one log cycle after recession becomes nearly linear on a semilog hydrograph. RECESS is based on a continuous-recession hydrograph. An interactive, repetitive process is used to select periods of continuous recession. A period of at least 10 years of record is recommended because only 5 to 10 suitable recessions may occur in a decade. The user can select the number of days required for the detection of a recession period. If too many days are chosen, few periods may be found; but if too few days are chosen, many periods may be found, requiring some periods to be skipped in the analysis. A reasonable range of days is 10 to 20. RECESS then detects and displays periods of recession from which the user selects a nearly linear segment to be included in the analysis. The rough guideline is for 20 to 30 periods of recession to be selected; RECESS allows a maximum of 50 recession periods. After all recession segments have been selected, the user can elect to discard any outliers in the estimated index values. Outliers could be caused by prolonged periods of slight precipitation or slight regulation if the streamflow is small. The output from RECESS includes the minimum, median, and maximum recession indices for the segments used in the final analysis. The median recession index from RECESS was used as input for the RORA program.

RORA was used to obtain an estimate of the mean rate of net ground-water recharge. RORA requires an estimated recession index. Although uncertainty is inherent in the determination of the recession index, this uncertainty may not be a problem because RORA is not highly sensitive to the index value. Before computations, RORA designates the number of days that fit a requirement for antecedent recession. The user can increase the number of antecedent days so as to reduce the effect of errors resulting from direct-surface runoff; however, an increase in antecedent days may degrade results by reducing the number of peaks detected. RORA works best with time scales of 3 months or more and is most reliable for periods of a year or more.

PART was used to partition streamflow and, thereby, estimate a daily record of base flow under the streamflow hydrograph. When PART is applied to a long period of record, the result is an estimate of the rate of mean ground-water discharge. The program uses antecedent recession to designate days when streamflow represents base flow. Small basins may be problematic for PART because the antecedent days cannot be defined as less than 1. Although the program can give results for individual months or multiple-month periods, Rutledge (1998) suggests that PART be used for periods of at least 1 year. The output from PART includes the mean streamflow, mean base flow (ground-water discharge), and the mean base-flow index (MBI), which is a the ratio of mean base flow to mean streamflow.

Selection of sites

Daily surface-water data are available for 377 active and discontinued streamflow-gaging stations in Ohio. The primary selection criteria for this study were based on the requirements of the RECESS-RORA-PART programs listed earlier. Of these 377 stations, 93 met the criteria for period of record, regulation, and drainage area. An additional 10 stations were included that met the first 2 of these criteria but somewhat exceeded the drainage-area requirement, ranging from 503 to 685 mi^2. These 103 stations (fig. 1) were the primary data set for estimating ground-water recharge rates and are hereafter referred to as the long-term continuous-record (LTCR) stations.

The LTCR stations were arbitrarily divided between three people for analysis with RECESS. One analyst ran 46 stations, the second ran 30, and the third, 27. The stations were divided such that no person analyzed all the sites in any given area. Moreover, an effort was made to ensure that if multiple stations were located on a single river, the stations were analyzed by different people. (See appendix A for quality-control data).

Before recession segments are selected, the months of interest are chosen; RECESS then will detect only segments that begin in those specified months. Winter months are suggested as target months because the results represent recessions during periods of low riparian evapotranspiration (Rutledge, 1998). A possible concern with using winter streamflow records in northern States is that stream freezeover may limit the records available for selecting segments. Thus, the longer the period of record for a station (spanning warm years and cold) the greater the odds that sufficient winter records will be available for the program. In this study, the months of November through February were used for all sites.

Both RORA and PART are more automated than RECESS. The only user-defined option involves a choice to increase the number of antecedent days used in RORA. In this study, the default conditions were used in RORA and PART for all stations.

Another set of 30 stations was selected for use with the PART program only. For these 30 stations, the length of record was insufficient to be used with RECESS but was sufficient for PART. Hereafter, these stations are referred to as the short-term continuous-record (STCR) stations. The drainage areas for 29 of these 30 stations ranged from 1.4 to 394 mi^2, and one station had a drainage area of 644 mi^2. On the basis of results for the LTCR stations, ground-water recharge rates were estimated for these STCR stations.

Another set of 28 stations, which only have low-flow partial data (Schwartz, 1985), were selected for testing the method of estimating ground-water recharge from basin characteristics. These stations are referred to as the low-flow partial-record (LFPR) stations. At these stations, two to three discharge measurements were made a year for several years that were used to define low-flow characteristics as a function of characteristics at index stations. LFPR stations used in this study were selected on the basis of their index stations. For each LFPR station, the index station had to be among the LTCR stations, and the general basin characteristics had to be similar for both the LTCR and LFPR stations.

Determination of basin characteristics

Six characteristics initially were considered for use in estimating ground-water recharge rates. These characteristics were the long-term mean annual precipitation rate, soil infiltration rate, glacial geology, thickness of glacial deposits, bedrock geology, and physiography. Other possible charateristics, such as land use and stream density, were not readily quantifiable at the statewide scale of this project and, therefore, were not considered.

The mean annual precipitation rate for each basin was determined by visually estimating an areally weighted average from a statewide precipitation isoline map by Harstine (1991) (fig. 2). For the soil and geologic characteristics, a statewide coverage was used to determine the associated characteristic properties. Basin characteristics were determined for only 96 of the 103 basins because 7 basins extended outside the State of Ohio and consistent GIS coverages were not readily available.

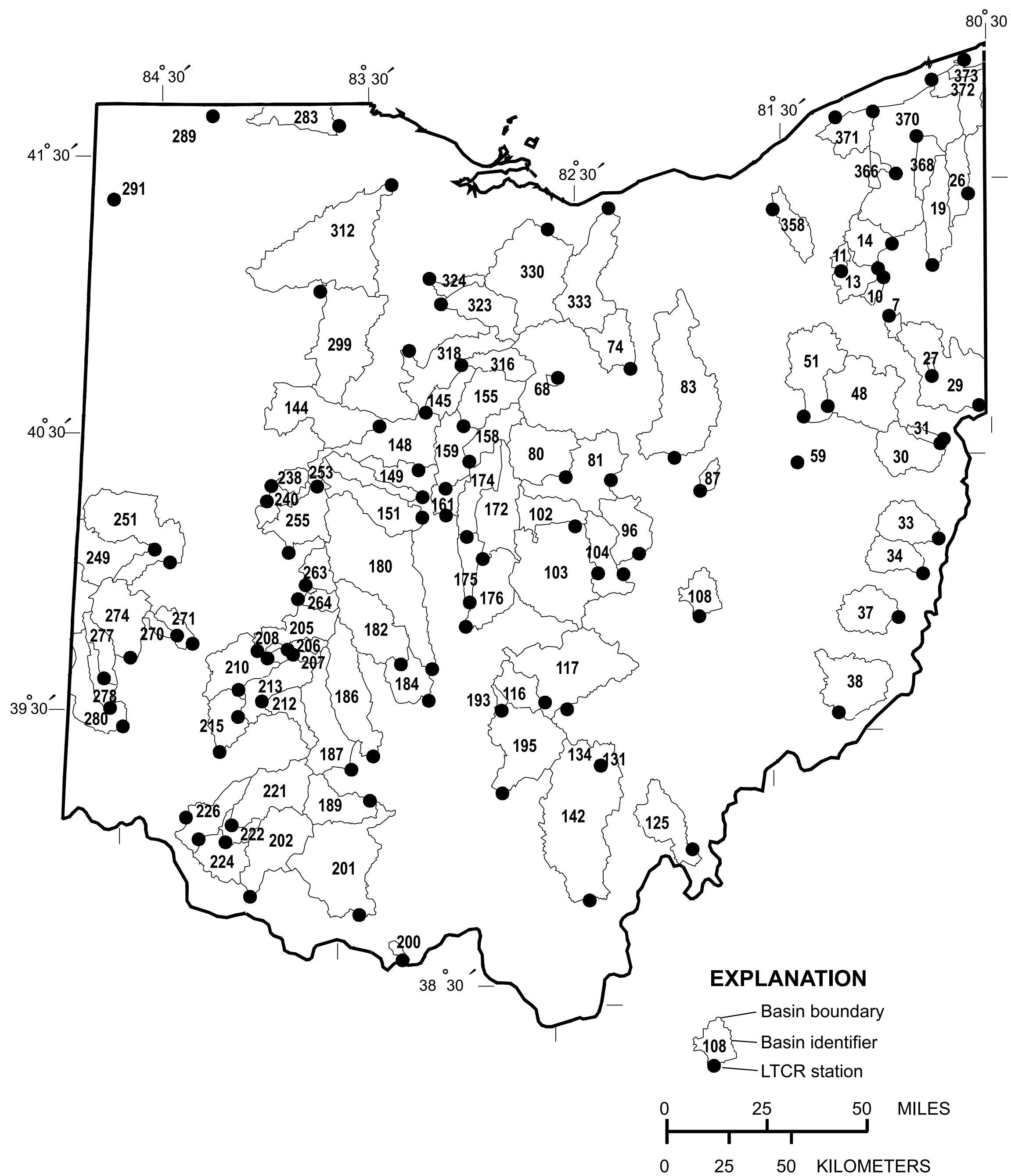

Figure 1. Locations of study basins with long-term continuous-record (LTCR) stations in Ohio.

Soil infiltration rates were based on the “hydgrp” element of the U.S. Department of Agriculture STATSGO data base (1994). The four hydgrp elements in the coverage were described as

A: high infiltration rates. Soils are deep, well drained to excessively well drained sands and gravels.

B: moderate infiltration rates. Soils are deep and moderately deep, moderately well and well drained with moderately coarse textures.

C: low infiltration rates. Soils have layers that impede infiltration or have moderately fine or fine textures.

D: very low infiltration rates. Soils are clayey, have a high water table, or are shallow over an impervious layer.

The four hydgrp elements were assigned numeric values from 1 to 4 with 1 being equal to A. Area-weighted averages then were calculated for the hydgrp elements, resulting in values ranging from 1.8 to 4.0. The infiltration-rate categories used in this study were based on these numeric values. The distribution of soil-infiltration rates is shown on figure 3.

The surficial glacial geology and glacial thickness coverages were obtained from the Ohio part of a 1:100,000 digital map of Quaternary deposits (Soller and Packard, 1998). The glacial geology (fig. 4) was divided into five categories as follows:

Till. Poorly sorted and generally unstratified material deposited in contact with glacial ice. Particle sizes range from clay to large boulders. Relative proportions of these size fractions vary greatly.

Coarse-grained stratified sediments. Material deposited in fluvial, glaciofluvial, deltaic, and outwash-plain settings. Generally layered sand and gravel with occasional silt and clay beds.

Fine-grained stratified sediments. Material deposited in quiet water, mostly proglacial lakes. Generally clay, silt, and very fine sand with lesser amounts of interbedded coarser material.

Patchy Quaternary sediments. Areas within the glacial limit but where Quaternary sediments do not blanket the surface. Patchy Quaternary sediment may be associated with exposures of bedrock, residuum, or colluvium (from nonglacial deposits). The proportion of glacial to nonglacial material ranges from numerous isolated exposures of bedrock in an area of thin till to patchy isolated exposures of till or stratified deposits on bedrock. Quaternary sediments may be absent or sparse near the limit of glaciation or in dissected areas within the glaciated region.

Other. Includes bedrock, nonglacial sediments, organic-rich sediments, or water bodies.

The glacial thickness was divided into five categories consisting of 0-50, 50-100, 100-200, 200-400, and 400-600 ft (fig. 5).

A statewide bedrock geology GIS coverage was unavailable; the only available statewide data were defined by geologic age rather than lithology. Therefore, the analysis of the effect of bedrock geologic characteristics on ground-water recharge was inadequate and not used for the study.

The physiography coverage, based on Fenneman and Johnson (1946), consisted of five categories in the coverage (physiographic sections): Eastern Lake Plain, Till Plain, Southern New York, Kanawha, and the Lexington Plain. Because physiographic sections largely are based on topographic relief, the use of the physiographic sections was an attempt to categorize the general topography in the State (fig. 6). The Eastern Lake Plain category represented low relief, but dissected; the Till Plain was low relief; Southern New York, moderate relief; Kanawha, moderate to high relief; and the Lexington Plain, deeply dissected.

Another set of GIS coverages was created that defined the drainage-basin boundaries associated with the gaging stations in all three data sets. The basin boundaries were obtained from an available coverage of watershed boundaries digitized from 1:24,000 topographic maps maintained by the USGS in Ohio. The characteristics of a given basin were determined by intersecting the basin boundary coverage with the coverage of each characteristic and then summing the areal percentages of each characteristic category for the basin.

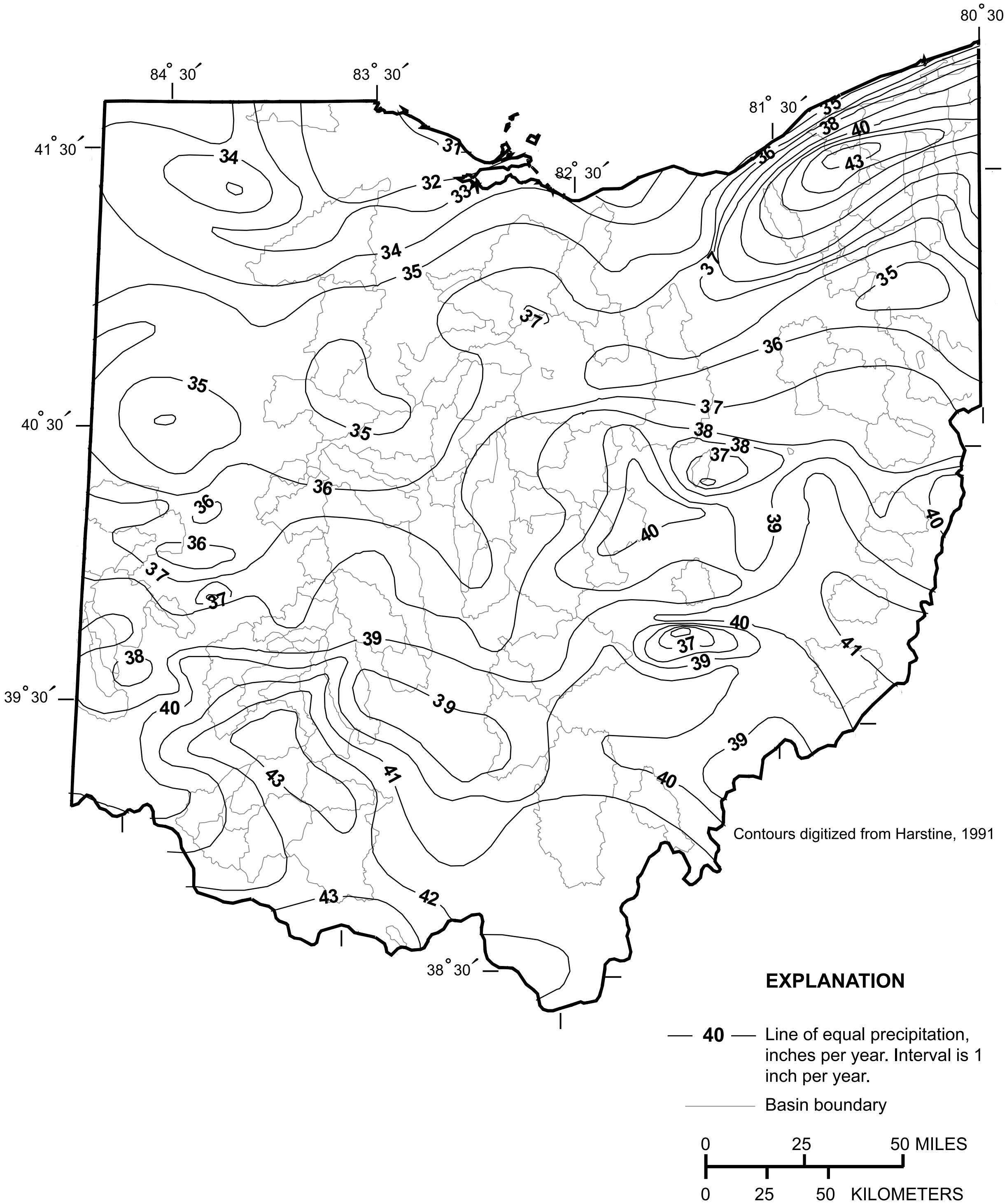

Figure 2. Distribution of annual precipitation in Ohio.

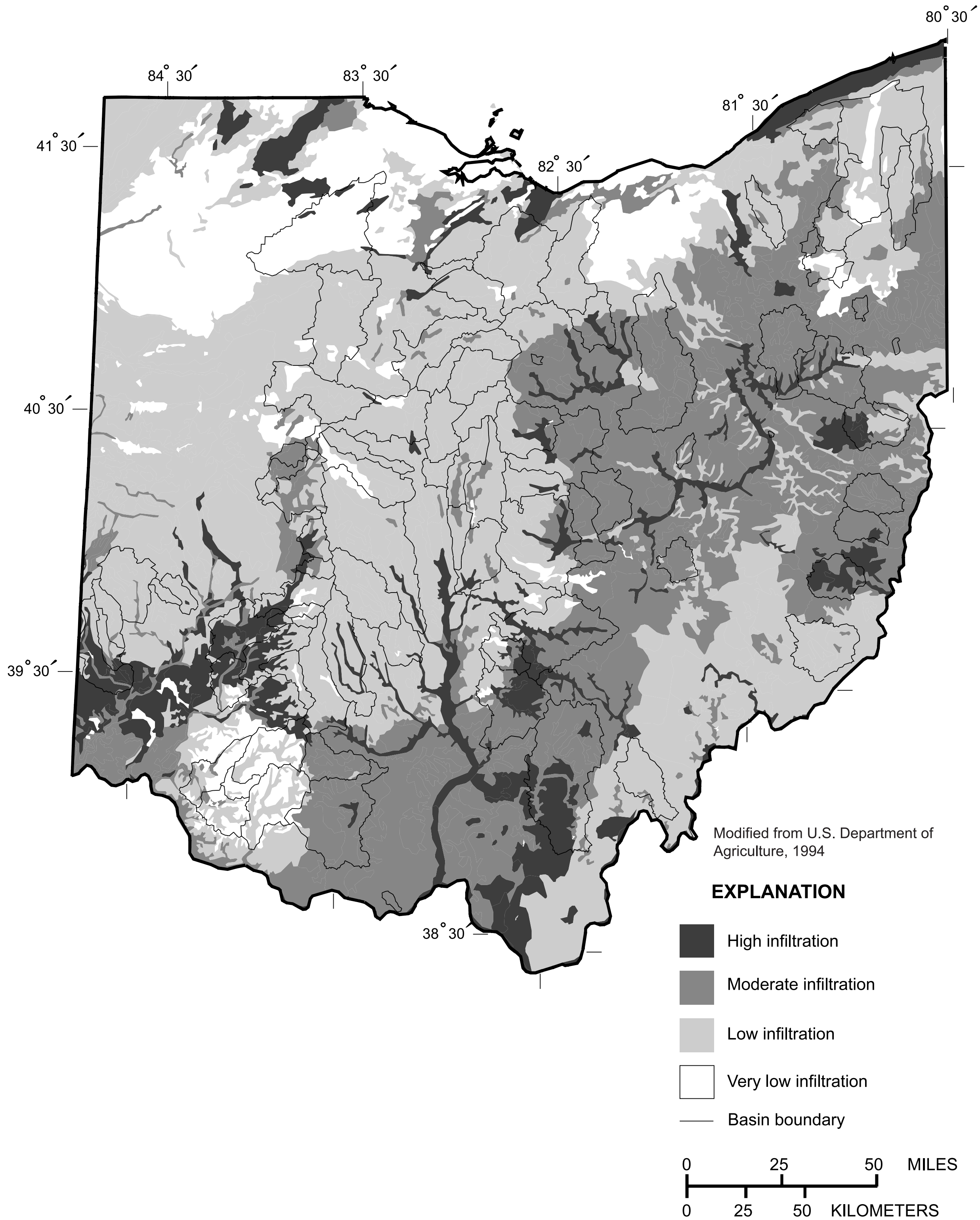

Figure 3. Distribution of soil-infiltration rates in Ohio.

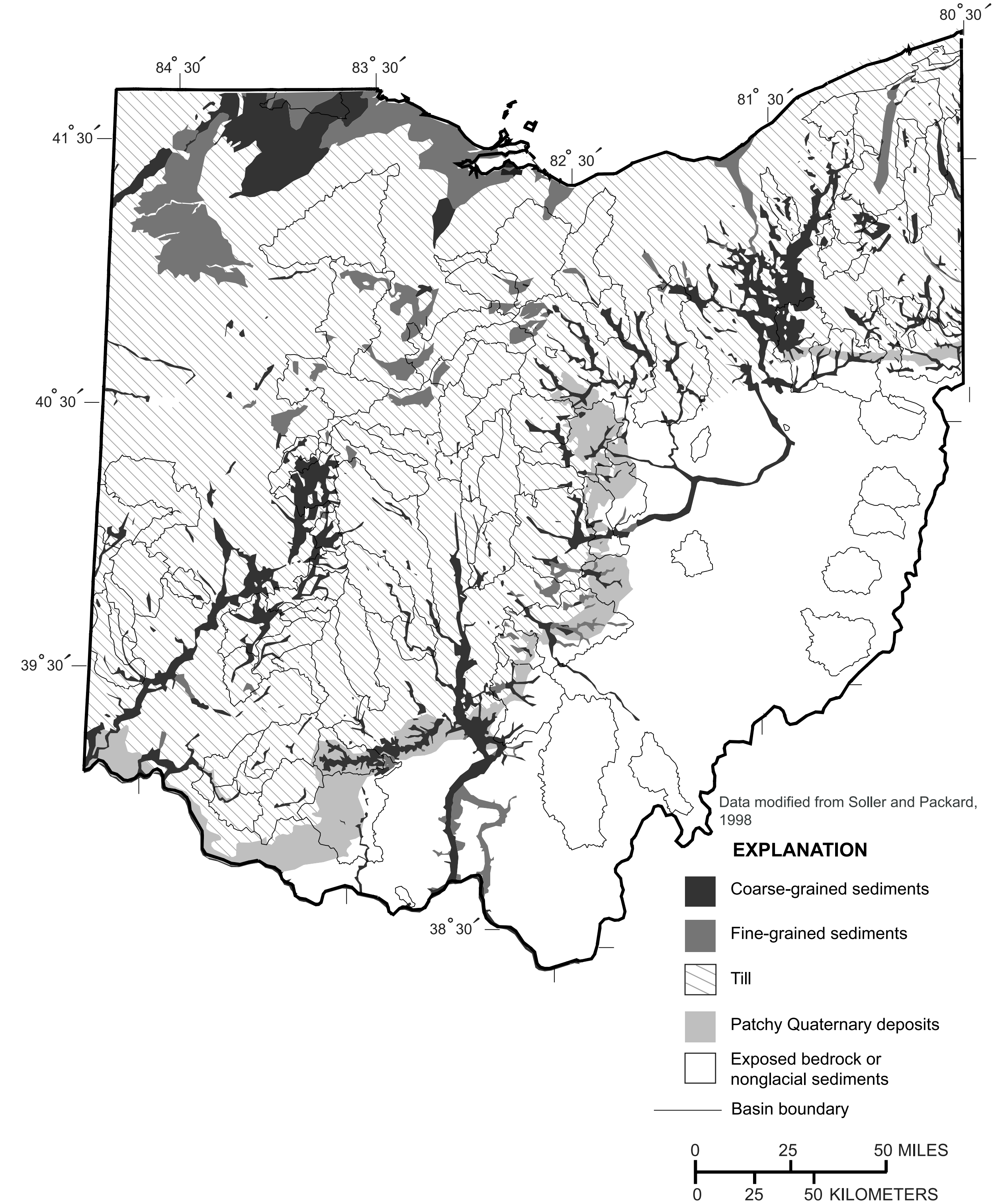

Figure 4. Distribution of glacial-sediment types in Ohio.

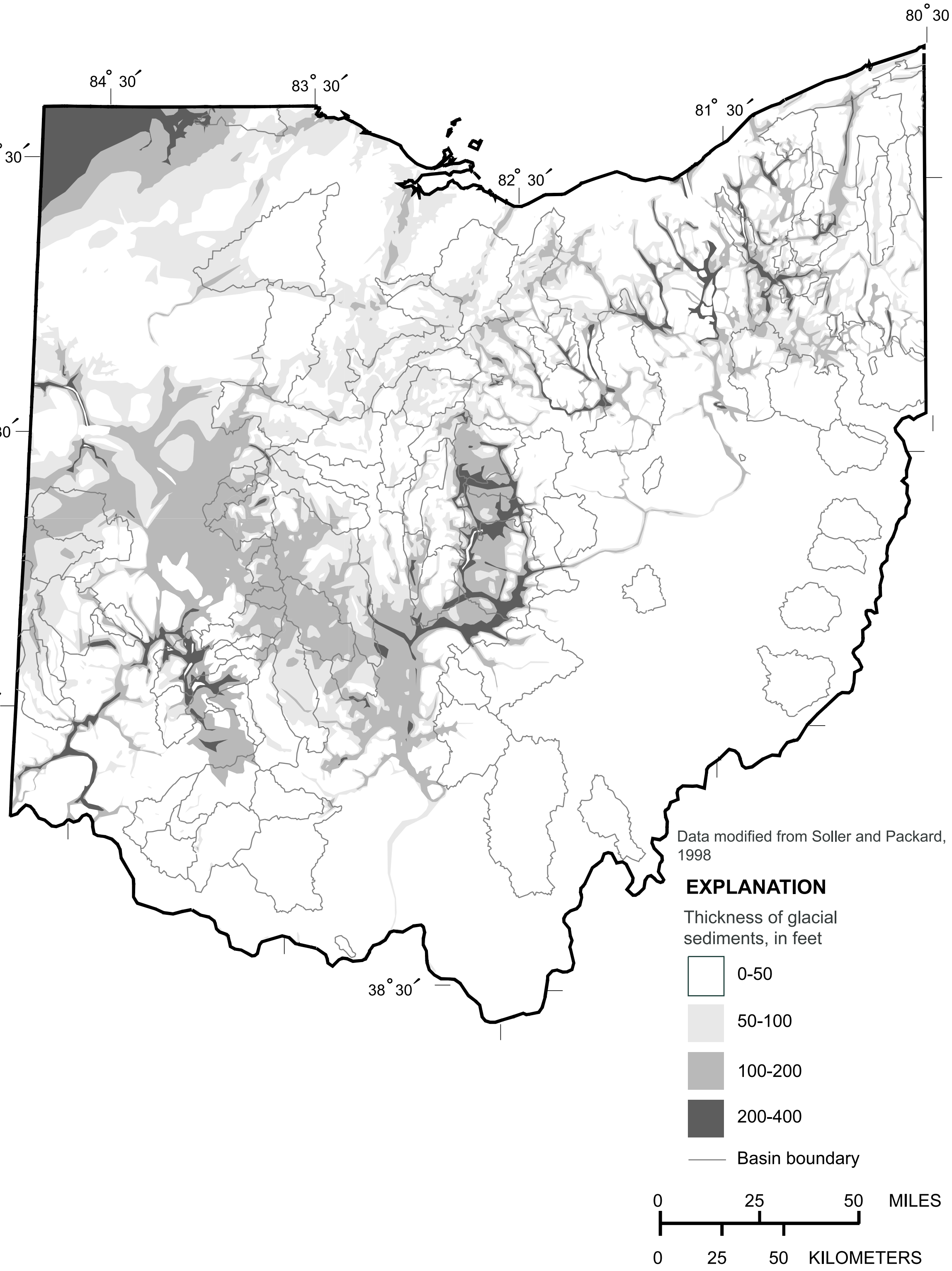

Figure 5. Distribution of thickness of glacial sediments in Ohio.

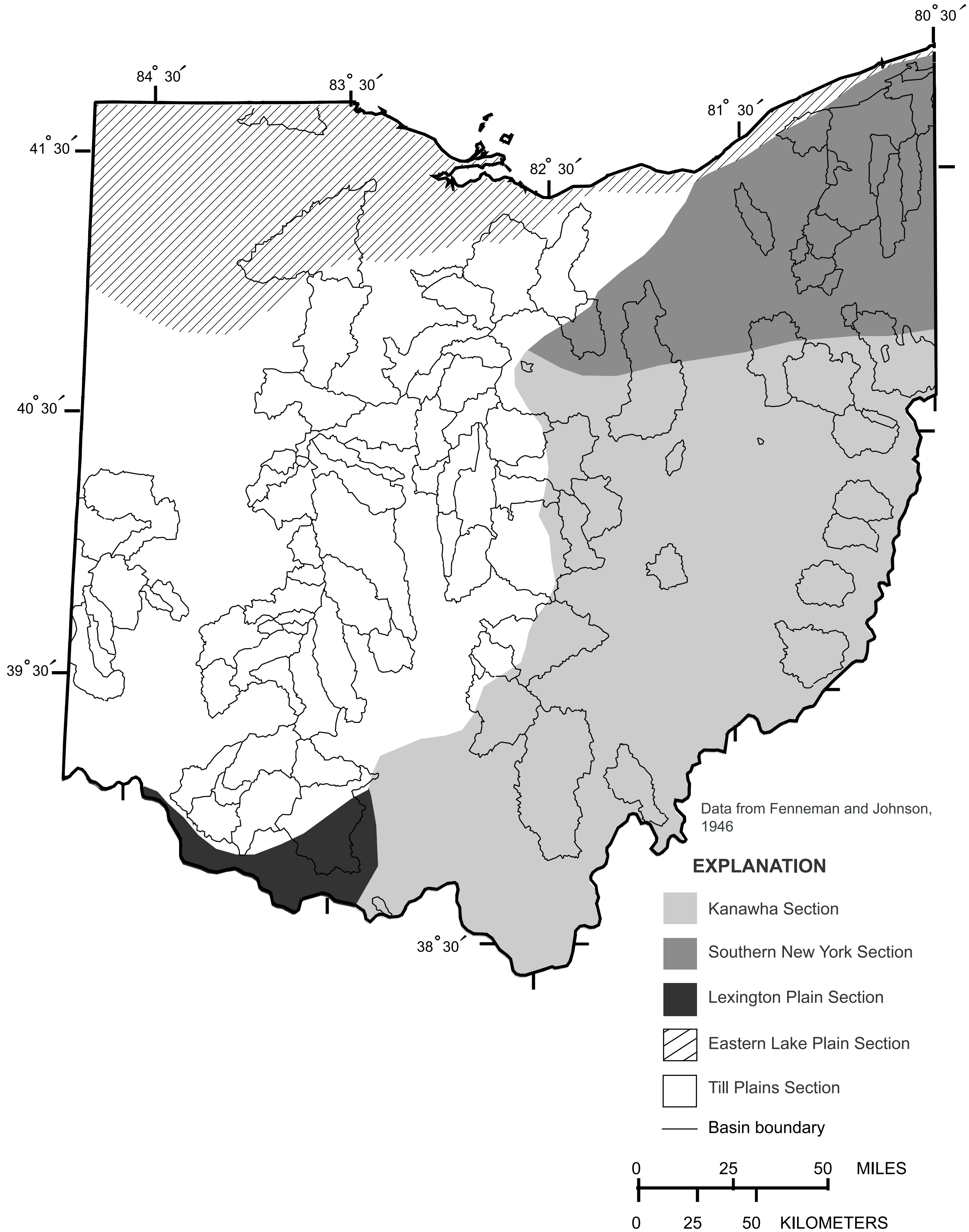

Figure 6. Distribution of physiographic regions (sections) in Ohio.

Data analysis

Boxplots were used to assess relations between basin characteristics and ground-water recharge estimates for the LTCR stations. In addition, the relation between the PART-derived MBI and the RORA-derived recharge estimates was evaluated. These relations then were used to estimate recharge rates for the STCR stations based on the PART-derived MBI and basin characteristics.

Basin characteristics then were used to estimate ground-water recharge rates for the LFPR stations. In addition, a recharge estimate was made on the basis of relations seen between low-flow statistics and results from the LTCR stations. Because the LFPR station and associated index station would be expected to have similar recharge rates, because of similar basin characteristics and base-flow statistics, the recharge estimates also were compared to the RORA-based recharge estimate for the index (LTCR) station.

Estimation of ground-water recharge rates

RORA was used to estimate the mean rate of effective ground-water recharge. These estimates are in inches per year for the basin upstream from the gaging station whose data were analyzed. Estimating recharge rates throughout Ohio required the use of data from gaging stations with many different periods of record. When making direct comparisons between basins, one should take periods of record into consideration because of the effect of potential climatic variations. For example, some periods of record could have been affected by a prolonged period of drought or unusual rainfall. The longer the period of record available, the less effect a short-term anomaly in precipitation should have. Although these period-of-record issues would be influential in analyses of a few basins or a small region, the statewide scope of this project resulted in a large data set, so these factors were not a problem for this study and were not explicitly examined.

Long-term continuous-record (LTCR) stations

The effective ground-water recharge estimates from RORA and the ground-water discharge estimates from PART are listed in table 1. The distribution of the recharge estimates is shown in figure 7. Ground-water recharge estimates range from 3 to 13 in/yr, with a median of 7 in/yr. Ground-water discharge estimates range from 2 to 11 in/yr, with a median of 6 in/yr. At all LTCR stations, the discharge estimate is equal to or less than the recharge estimate. Of the 103 stations, 76 have recharge and discharge estimates that are either equal or different by only 1 in/yr; at only four stations is the difference more than 2 in/yr. The relation between the recharge and discharge estimates is shown in figure 8. Rutledge (2000) notes that ground-water recharge and discharge estimates may be nearly equal at decadal time scales if other gains and losses are small in relation to recharge.

The PART program results also include a number called the mean base-flow index (MBI). The index is the ratio of mean base flow to mean streamflow. The MBI ranged from 17.0 to 81.1, with a median of 41 (table 1). The MBI correlates reasonably well with the ground-water recharge and discharge estimates (fig. 9) and, therefore, may be useful in estimating ground-water recharge rates for the STCR stations.

Basin characteristics. In Ohio, the mean annual precipitation ranges from less than 30 to nearly 44 in., with the highest rates in the southwestern and northeastern areas (fig. 2). Lake-effect snows account for much of the high precipitation rate in northeastern Ohio (Harstine, 1991). The estimated mean annual precipitation ranges from 33.2 to 43.5 in., with a median rate of 38.3 in. The estimated mean annual precipitation for each LTCR station is listed in table 1.

Many of the study basins are covered mostly in soils with moderate or low infiltration rates or a combination of these two categories (fig. 3; table 2, at back of report). Only eight basins have 35 percent or more coverage by soils with high infiltration rates. Coincidentally, only eight basins have 35 percent or more coverage by soils with very low infiltration rates.

The percentages of till and coarse- and fine-grained stratified sediments were determined for basins in the glaciated parts of Ohio. Percentages of two additional categories, patchy Quaternary sediments and "other," were assigned for basins near the boundary of the glaciated region or in unglaciated parts of the State (fig. 4; table 3, at back of report). Of the 96 basins for which characteristics were determined, 71 are entirely within the glaciated region and 13 basins are entirely outside the glaciated region of Ohio. Of these 71 basins, all but 7 have till covering 80 percent or more of the basin. Of all 96 basins, only 8 have coarse-grained sediments covering 20 percent or more of the basin. Patchy Quaternary sediments cover more than 20 percent of six basins.

Table 1. Results of the RORA and PART programs and precipitation estimates for the long-term continuous-record (LTCR) stations in Ohio

[mi^2, square miles; in/yr, inches per year; stations with no precipitation estimates were not included in the basin-characteristics components of the project]

Basin identifier (fig. 1)	Station name	Station number	Drainage area (mi^2)	Years of record used	Ground-water recharge (in/yr)	Ground-water discharge (in/yr)	Mean base-flow index	Precipitation (in/yr)
7	Mill Creek near Berlin Center	03089500	19.1	1942-70	5	4	31.1	35.5
10	Kale Creek near Pricetown	03092000	21.9	1941-93	5	4	25.2	35.3
11	West Branch Mahoning River near Ravenna	03092090	21.8	1965-93	9	8	42.9	38.0
13	West Branch Mahoning River near Newton Falls	03092500	96.3	1927-65	6	5	37.3	35.5
14	Eagle Creek at Phalanx Station	03093000	97.6	1937-98	8	7	45.5	38.0
19	Mosquito Creek at Niles	03096000	138	1929-43	6	4	38.0	38.0
26	Pymatuning Creek at Kinsman	03102950	96.7	1965-94	12	9	51.0	39.5
27	Lisbon Creek at Lisbon	03109000	6.19	1946-62	8	7	53.3	36.5
29	Little Beaver Creek near East Liverpool	03103500	496	1916-97	9	8	55.4	
30	Yellow Creek near Hammondsville	03110000	147	1940-98	10	9	60.5	37.7
31	Yellow Creek at Hammondsville	03110500	164	1915-35	11	8	52.2	37.5
33	Short Creek near Dillonvale	03111500	123	1941-98	12	10	71.4	39.5
34	Wheeling Creek below Blaine	03111548	97.7	1983-98	13	11	69.6	39.7
37	Captina Creek at Armstrongs Mills	03114000	134	1926-35[a] 1958-98	10	9	49.8	41.3
38	Little Muskingum River at Bloomfield	03115400	210	1958 -81	8	7	41.5	40.5
48	Sandy Creek at Waynesburg	03117500	253	1939-98	10	9	63.0	37.3
51	Sandy Creek at Sandyville	03119000	481	1924-46	9	8	58.9	37.0
59	Home Creek near New Philadelphia	03125000	1.64	1935-79	6	5	48.2	38.3
68	Touby Run at Mansfield	03130500	5.44	1945-78	6	5	39.5	36.5
74	Jerome Fork at Jeromeville	03134000	120	1925-49	5	4	36.6	36.3
80	Kokosing River at Mount Vernon	03136500	202	1953-98	10	8	56.7	38.0
81	Kokosing River at Millwood	03137000	455	1921-74	8	8	53.1	38.3
83	Killbuck Creek at Killbuck	03139000	464	1931-98	9	8	65.0	36.7
87	Mill Creek near Coshocton	03140000	27.2	1936-98	9	8	54.8	37.7
96	Wakatomika Creek near Frazeysburg	03144000	140	1937-97	9	8	54.5	40.0
102	North Fork Licking River at Utica	03146000	116	1940-81	8	7	36.8	38.0
103	Licking River near Newark	03146500	537	1939-98	8	8	49.9	38.5
104	Licking River at Toboso	03147000	672	1921-61	8	6	47.8	38.7
108	Salt Creek near Chandlersville	03149500	75.7	1935-47	8	7	44.5	39.3
116	Clear Creek at Rockbridge	03157000	89.0	1940-97	9	8	59.8	39.0
117	Hocking River at Enterprise	03157500	459	1931-98	7	7	53.5	39.2
125	Shade River at Chester	03159540	156	1966-83[a] 1985-97	7	6	36.8	40.5
131	Sandy Run near Lake Hope	03201600	.98	1970-81	11	8	50.3	40.1
134	Big Four Hollow near Lake Hope	03201700	1.01	1970-83	8	7	46.0	40.1
142	Raccoon Creek at Adamsville	03202000	585	1916-34[a] 1939-84 1992-97	8	7	48.7	41.0
144	Scioto River at LaRue	03217500	257	1927-34[a] 1939-50	5	4	33.3	35.0
145	Little Scioto River above Marion	03218000	72.4	1938-72	5	4	43.3	35.7
148	Scioto River near Prospect	03219500	567	1925-98	5	4	38.2	35.5
149	Bokes Creek near Warrensburg	03219590	83.2	1983-96	5	4	32.4	35.5
151	Mill Creek near Bellepoint	03220000	178	1943-98	4	3	25.4	36.0
155	Olentangy River at Claridon	03223000	157	1947-97	6	5	35.8	36.3
158	Whetstone Creek near Ashley	03224500	98.7	1954 -74	6	5	36.8	36.7

Table 1. Results of the RORA and PART programs and precipitation estimates for the long-term continuous-record (LTCR) stations in Ohio

[mi^2, square miles; in/yr, inches per year; stations with no precipitation estimates were not included in the basin-characteristics components of the project]

Basin identifier (fig. 1)	Station name	Station number	Drainage area (mi^2)	Years of record used	Ground-water recharge (in/yr)	Ground-water discharge (in/yr)	Mean base-flow index	Precipitation (in/yr)
159	Olentangy River near Delaware	03225500	393	1924 -34[a] 1938-50	5	4	31.9	36.3
161	Olentangy River at Stratford	03226500	445	1934-58	4	4	31.3	36.5
172	Big Walnut Creek at Central College	03228500	190	1938-53	5	4	26.0	37.5
174	Alum Creek at Africa	03228805	122	1963-73	6	4	31.0	37.3
175	Alum Creek at Columbus	03229000	189	1923-35* 1938-73	5	4	31.8	37.0
176	Big Walnut Creek at Rees	03229500	544	1922-34[a] 1939-55	5	4	30.6	37.5
180	Big Darby Creek at Darbyville	03230500	534	1921-35[a] 1938-98	6	6	46.2	37.5
182	Deer Creek at Mount Sterling	03230800	228	1966-81	9	7	52.2	38.5
184	Deer Creek at Williamsport	03231000	333	1927-34[a] 1939-55	6	5	44.6	38.7
186	Paint Creek near Greenfield	03232000	249	1927-34[a] 1940-55 1967-80	7	6	48.5	39.3
187	Rattlesnake Creek at Centerfield	03232300	209	1971-81	10	8	46.4	41.0
189	Rocky Fork near Barretts Mills	03232500	140	1939-99	9	7	50.2	43.0
193	Salt Creek at Tarlton	03235000	11.5	1946-61	5	4	35.1	39.3
195	Salt Creek near Londonderry	03236000	286	1939-49	8	6	44.4	39.5
200	Upper Twin Creek at McGaw	03237280	12.2	1964-97	9	7	44.6	43.5
201	Ohio Brush Creek near West Union	03237500	387	1927-34[a] 1941-97	5	4	26.0	42.5
202	White Oak Creek near Georgetown	03238500	218	1923-35[a] 1939-99	4	3	17.7	42.3
205	Little Miami River near Oldtown	03240000	129	1953-97	9	8	65.1	38.0
206	North Fork Massie Creek at Cedarville	03240500	28.9	1955-68	9	8	61.9	38.5
207	South Fork Massie Creek near Cedarville	03241000	17.1	1954-68	9	8	52.1	38.7
208	Massie Creek at Wilberforce	03241500	63.2	1952-98	9	8	59.6	38.5
210	Little Miami River near Spring Valley	03242050	366	1968-83	12	10	65.9	39.0
212	Anderson Fork near Burlington	03242200	77.8	1968-83	8	7	45.9	42.0
213	Caesar Creek at Harveysburg	03242300	209	1960-75	8	6	43.8	39.8
215	Little Miami River near Fort Ancient	03242500	680	1940-50	8	7	47.6	40.0
221	East Fork Little Miami River near Marathon	03246200	195	1968-83	6	4	24.4	42.8
222	East Fork Little Miami River at Williamsburg	03246500	237	1961-73	4	3	18.7	42.3
224	East Fork Little Miami River near Batavia	03247050	352	1965-76	5	4	22.8	42.0
226	East Fork Little Miami River at Perintown	03247500	476	1925-49	4	3	17.0	41.8
238	Bokengehalas Creek near DeGraff	03260700	36.3	1958-90	10	9	69.1	35.8
240	Stony Creek near DeGraff	03260800	59.1	1958-75	9	8	66.8	37.3
249	Greenville Creek near Bradford	03264000	193	1931-98	8	7	52.9	
251	Stillwater River at Pleasant Hill	03265000	503	1917-27[a] 1935-97	6	5	39.9	
253	Mad River at Zanesfield	03266500	7.31	1946-79	10	9	65.0	35.7
255	Mad River at Urbana	03267000	162	1939-99	11	10	81.1	36.5
263	Buck Creek at New Moorfield	03268000	65.3	1943-57	11	10	75.2	38.7
264	Beaver Creek near Springfield	03268500	39.2	1942-58	8	8	58.8	38.0
270	Wolf Creek at Trotwood	03270800	22.7	1963-86	7	6	40.4	38.3

Table 1. Results of the RORA and PART programs and precipitation estimates for the long-term continuous-record (LTCR) stations in Ohio

[mi^2, square miles; in/yr, inches per year; stations with no precipitation estimates were not included in the basin-characteristics components of the project]

Basin identifier (fig. 1)	Station name	Station number	Drainage area (mi^2)	Years of record used	Ground-water recharge (in/yr)	Ground-water discharge (in/yr)	Mean base-flow index	Precipitation (in/yr)
271	Wolf Creek at Dayton	03271000	68.7	1939-50[a] 1986-95	6	5	42.2	38.0
274	Twin Creek near Ingomar	03271800	197	1962-98	7	5	39.7	38.5
277	Sevenmile Creek at Camden	03272700	69.0	1971-97	8	7	47.4	39.0
278	Sevenmile Creek at Collinsville	03272800	120	1960-72	7	5	45.9	38.3
280	Fourmile Creek near Hamilton	03273500	307	1937-55	6	5	40.1	38.8
283	Ottawa River at Toledo	04177000	150	1976-98	6	5	40.2	
289	Bean Creek at Powers	04184500	206	1940-81	8	7	65.4	
291	Unnamed Tributary to Lost Creek near Farmer	04185440	4.23	1986-97	5	4	25.9	34.0
299	Blanchard River near Findlay	04189000	346	1923-34[a] 1940-98	4	3	30.9	35.5
312	Portage River at Woodville	04195500	428	1929-35[a] 1940-51	3	3	26.5	33.2
316	Sandusky River near Bucyrus	04196000	88.8	1925-35[a] 1938-51 1964-81	6	4	32.4	36.2
318	Sandusky River near Upper Sandusky	04196500	298	1921-81	5	4	36.1	36.0
323	Honey Creek at Melmore	04197100	149	1976-98	6	4	32.4	36.5
324	Rock Creek at Tiffin	04197170	34.6	1983-98	4	3	26.2	35.7
330	Huron River at Milan	04199000	371	1951-80	5	4	35.5	36.0
333	Vermilion River near Vermilion	04199500	262	1950-81	5	4	32.6	35.0
358	Tinkers Creek at Bedford	04207200	83.9	1963-97	13	10	48.0	40.2
366	Phelps Creek near Windsor	04210000	25.6	1942-59	7	5	29.1	42.0
368	Rock Creek near Rock Creek	04211000	69.2	1942-66	6	4	28.2	41.0
370	Grand River near Madison	04212000	581	1923-34[a] 1939-73	8	6	35.6	41.0
371	Grand River near Painesville	04212100	685	1975-92[a] 1995-97	10	8	39.3	40.5
372	Ashtabula River near Ashtabula	04212500	121	1924-35[a] 1939-47 1950-79	6	5	31.3	
373	Conneaut Creek at Conneaut	04213000	175	1923-35[a] 1954-97	10	8	38.4	

[a]Weighted averages are reported for recharge, discharge, and mean base-flow index because of the discontinous periods of record.

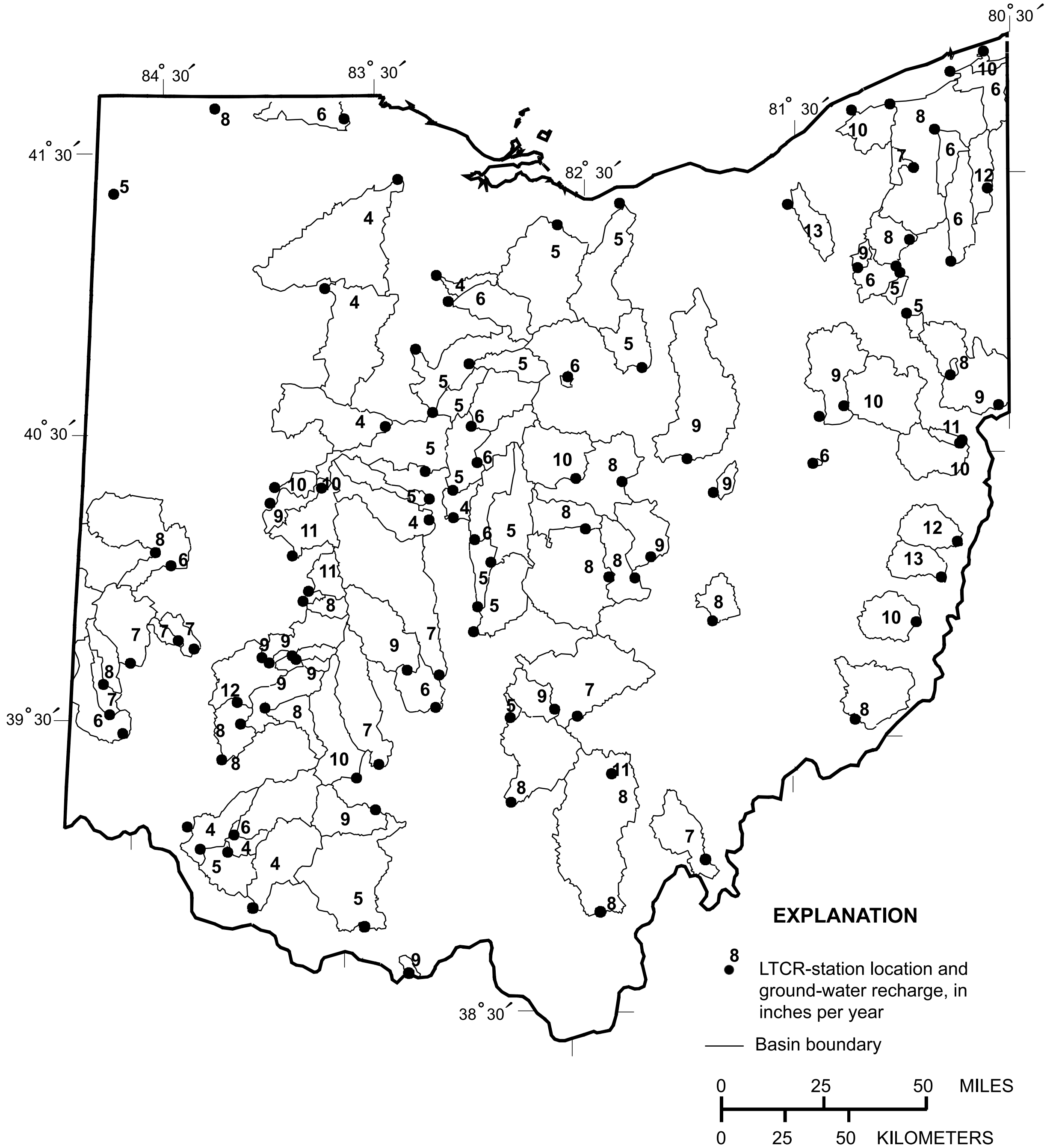

Figure 7. Distribution of ground-water recharge estimates for long-term continuous-record (LTCR) stations in Ohio.

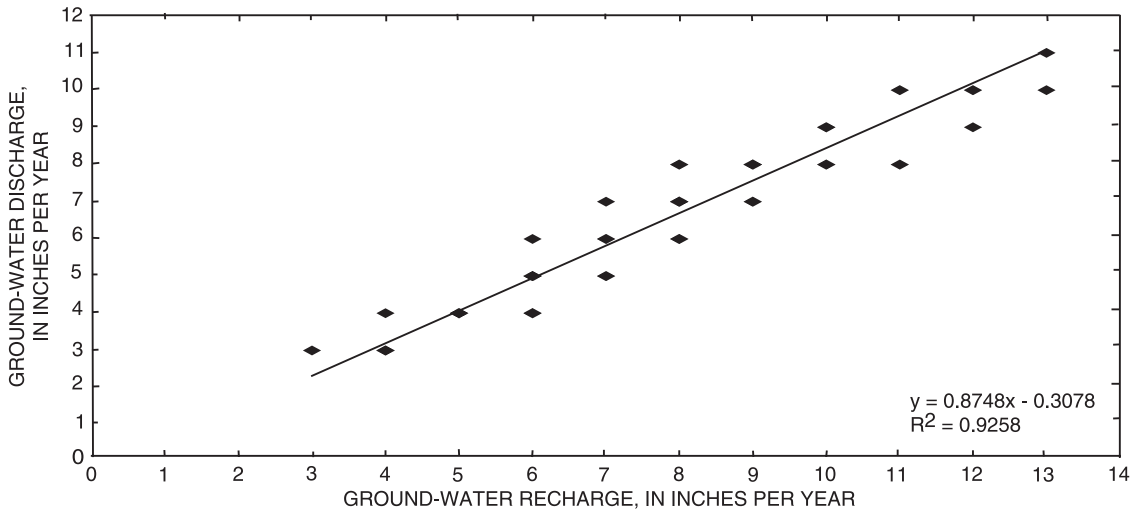

Figure 8. Relation between ground-water recharge and discharge estimates for the long-term continuous-record (LTCR) stations in Ohio.

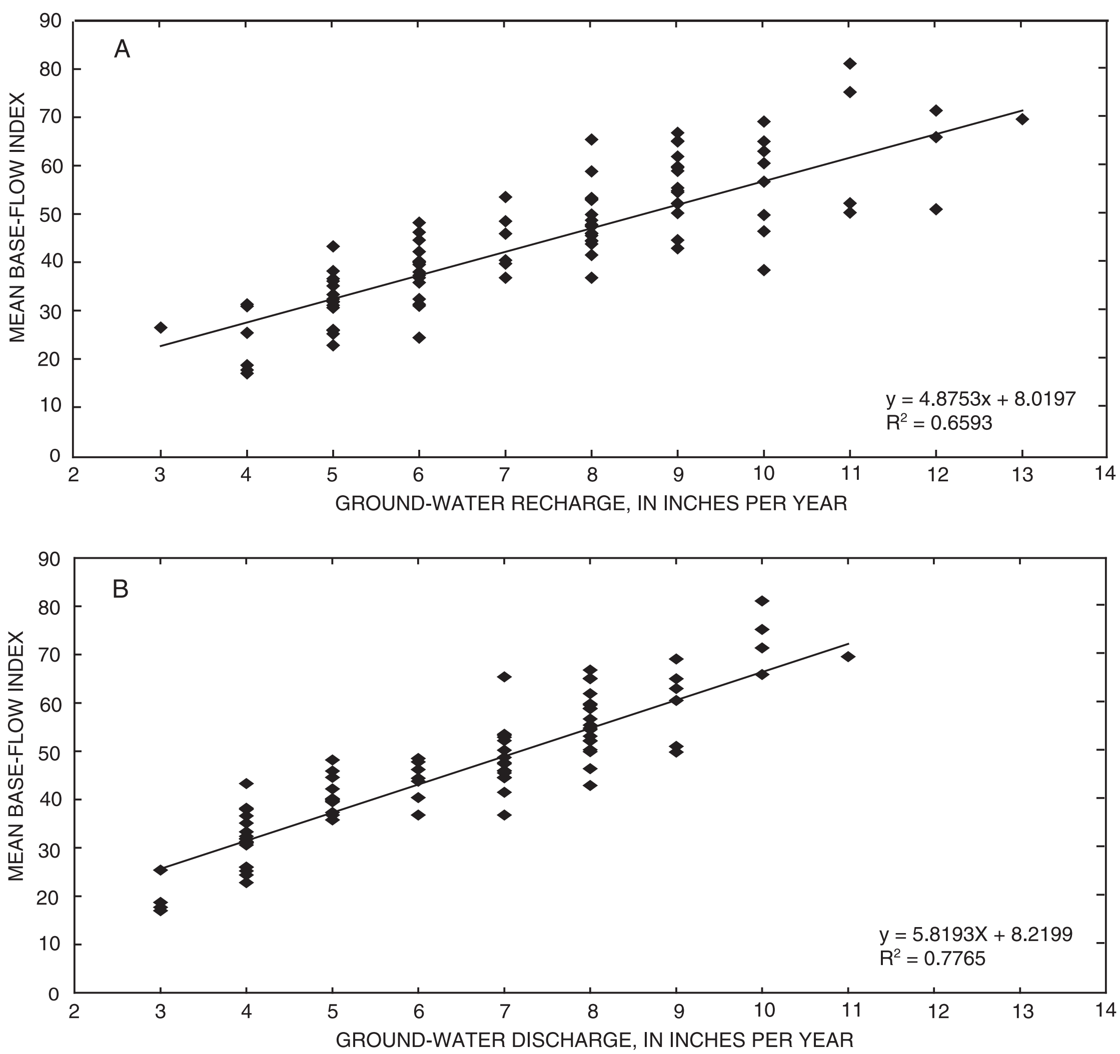

Figure 9. Relation of estimated (A) ground-water recharge and (B) ground-water discharge to mean base-flow index (MBI) for the long-term continuous-record (LTCR) stations in Ohio.

The thickness of glacial sediments in Ohio is variable, because of numerous buried bedrock valleys infilled with thick glacial deposits (fig. 5). Not surprisingly, most basins are covered by a large percentage of sediments the 0-50 ft thickness category (table 3), particularly because all basins in the unglaciated parts of Ohio also fall within this category. Only 11 basins have greater than 50 percent coverage in glacial deposits 100 ft or thicker, and only 3 of these 11 have more than 90 percent coverage.

Because the State is composed of only five physiographic sections, four of which are relatively large (fig. 6) most basins fall completely within one section. Of the 96 LTCR basins, 52 are 100 percent in the Till Plains Section, 19 are 100 percent in the Kanawha Section, 11 are 100 percent in the Southern New York Section, and 1 is 100 percent in the Eastern Lake Plain Section (table 4, at back of report). Only one basin is even partially within the Lexington Plain. As a result, most basins fall predominately in the low-relief category.

Relation of basin characteristics to ground-water recharge estimates.

Precipitation. In general, basins with low precipitation also have low estimated ground-water recharge rates. For basins with precipitation less than 36.6 in/yr, recharge estimates generally are 6 in/yr or less (fig. 10). The biggest exceptions to this pattern are the Bokengehalas Creek Basin (238) and the two Mad River Basins (253, 255). Bokengehalas Creek and particularly the Mad River at Urbana (255) have greater proportions of coarse glacial sediments than most basins (table 3), a fact that may account for the unusually high recharge rate given the relatively low precipitation in these basins.

The relatively high recharge (10 in/yr) in the Mad River at Zanesfield Basin with the relatively low precipitation (35.7 in/yr) cannot be similarly explained, because the percentage of coverage with coarse glacial sediments is low (6 percent). Previous investigators have found that thick sand and gravel deposits within bedrock valleys along the Mad River contribute to the unusually large base-flow component in the Mad River (Pettyjohn and Henning, 1979; Koltun, 1995). In addition, Sheets and Yost (1994) estimated that 60 to 80 percent of the base flow in the Mad River is from flow from the carbonate bedrock; they note that the Mad River Valley probably functions as a discharge area for the carbonate rocks.

In basins with precipitation greater than 36.6 in/yr, the recharge rate generally is greater than 6 in/yr and commonly greater than 7 in/yr (fig. 10). Excep-

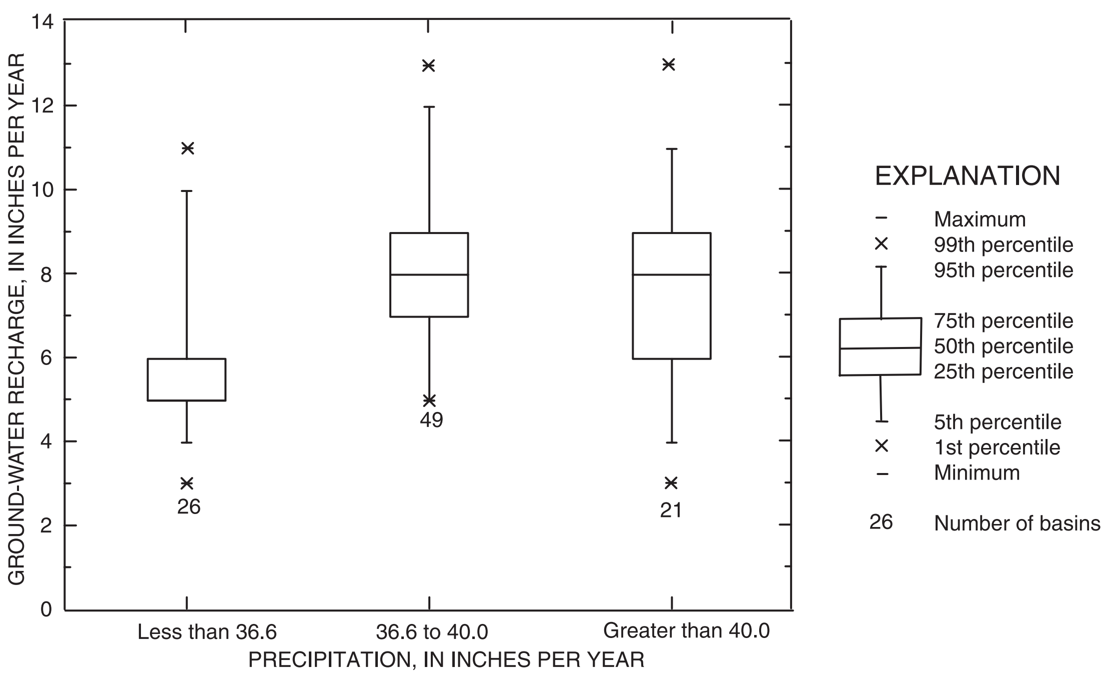

Figure 10. Relation between ground-water recharge and precipitation for the long-term continuous-record (LTCR) stations in Ohio.

tions, with lower recharge values, are Salt Creek at Tarlton (193), Ohio Brush Creek (201), White Oak Creek (202), and the four basins of the East Fork of the Little Miami (221, 222, 224, 226) (table 1). All of these basins, except Ohio Brush Creek, are covered extensively in till, greater than 90 percent (table 3). Ohio Brush Creek has a 57 percent coverage of patchy Quaternary sediments. In addition, except for Ohio Brush Creek and Salt Creek, these basins are covered in greater than 50 percent of the very low infiltration soils (table 2), and except for Ohio Brush Creek, the combined coverage of soils with low and very low infiltration rates in the basins is over 90 percent. The combination of high percentages of till and low and/or very low infiltration soils may explain the low recharge estimates despite the high precipitation.

One feature of the Ohio Brush Creek Basin that may explain the relatively low recharge estimate is that 52 percent of this basin is in the Lexington Plain section. This physiographic section is described as being deeply dissected (Pettyjohn and Henning, 1979, p. 72). The steep topography may account for a greater surficial runoff than in areas with less relief. Pettyjohn and Henning (1979) also noted that base flow generally is low in this region.

Soils. The infiltration rates of the soils in a basin are an important factor in determining the ground-water recharge rate. Analysis of the 96 LTCR stations indicates that basins with soils having very low infiltration rates covering more than 20 percent of the basin have ground-water recharge rates of 7 in/yr or less and commonly 5 in/yr or less (fig. 11). Two basins, South Fork Massie Creek (207) and the Grand River near Madison (370), are exceptions. These two basins have 20 percent coverage with soils of very low infiltration rates but have estimated recharge rates of 9 in/yr and 8 in/yr, respectively (tables 1, 2). Most other basins in this group have much greater percentages of soils with very low infiltration rates (table 2). In basins where soils having high infiltration rates cover more than 20 percent of the basin, the recharge rate generally is 7 in/yr or more and commonly 8 in/yr or more (fig. 11).

Glacial geology. Another factor that appears to be related to the ground-water recharge rate is the geology of the glacial deposits in a basin (table 3). The percentage of coarse-grained glacial sediments in the basin seems to be the most useful glacial geology characteristic in estimating the recharge rate. If coarse deposits cover more than 10 percent of the basin, the

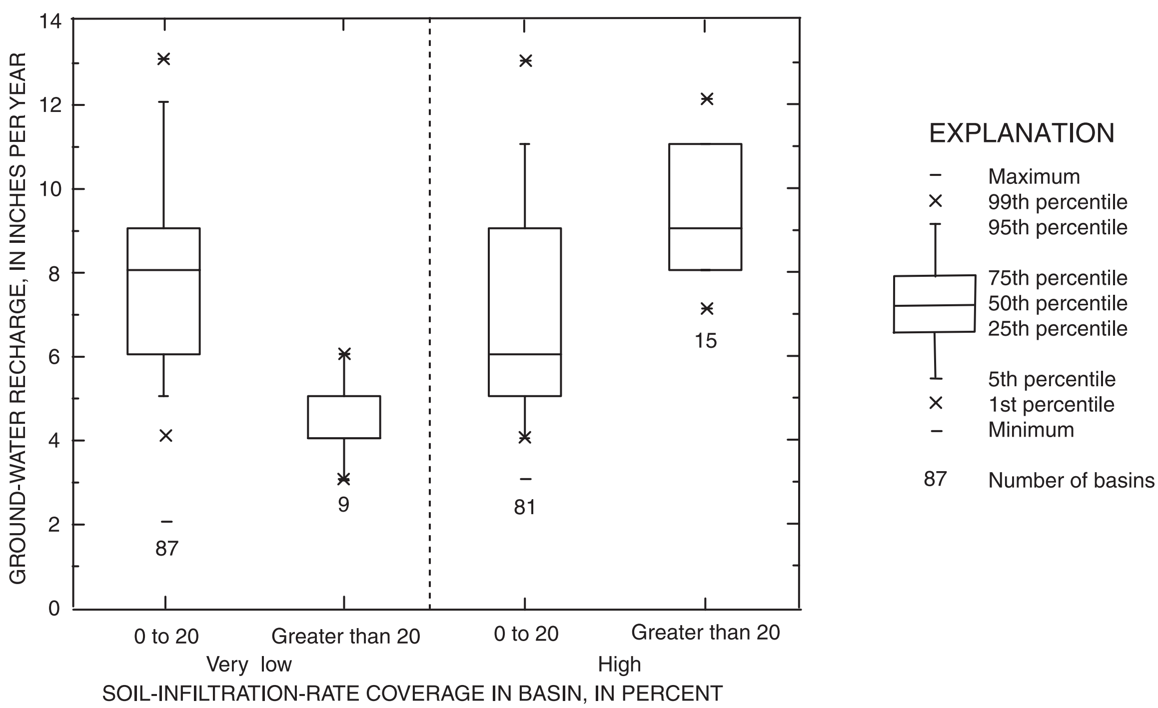

Figure 11. Relation between ground-water recharge estimates and soil characteristics for long-term continuous-record (LTCR) stations in Ohio.

recharge rate generally is above 8 in/yr, and if coarse deposits cover more than 20 percent, the rate generally is 9 in/yr or more (fig. 12). Three basins, Mill Creek (7), Jerome Fork (74), and the unnamed tributary to Lost Creek (291), are exceptions; however, all three of these basins have relatively low precipitation rates — 35.5, 36.3, and 34 in/yr, respectively (table 1).

The thickness of the glacial deposits in a basin also was considered as a possible factor in explaining ground-water recharge rates. When considered alone, the thickness of the glacial deposits seems to be a factor only when the deposits are 100 ft thick or more (fig. 13). When these thick glacial deposits cover more than 30 percent of the basin, the recharge generally is

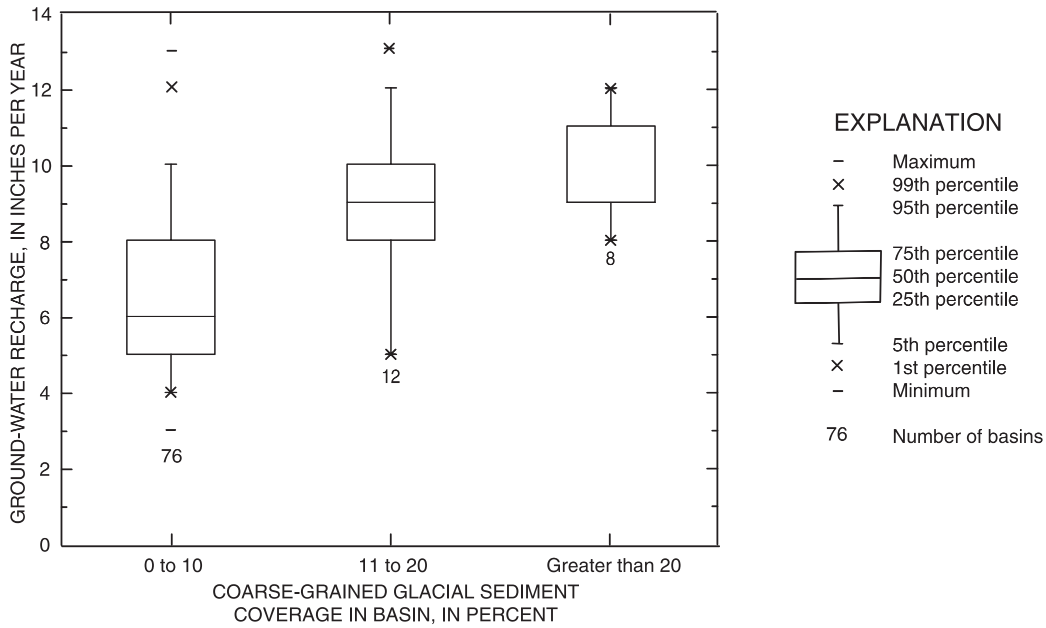

Figure 12. Relation between ground-water recharge estimates and glacial sediment characteristics for the long-term continuous record (LTCR) stations in Ohio.

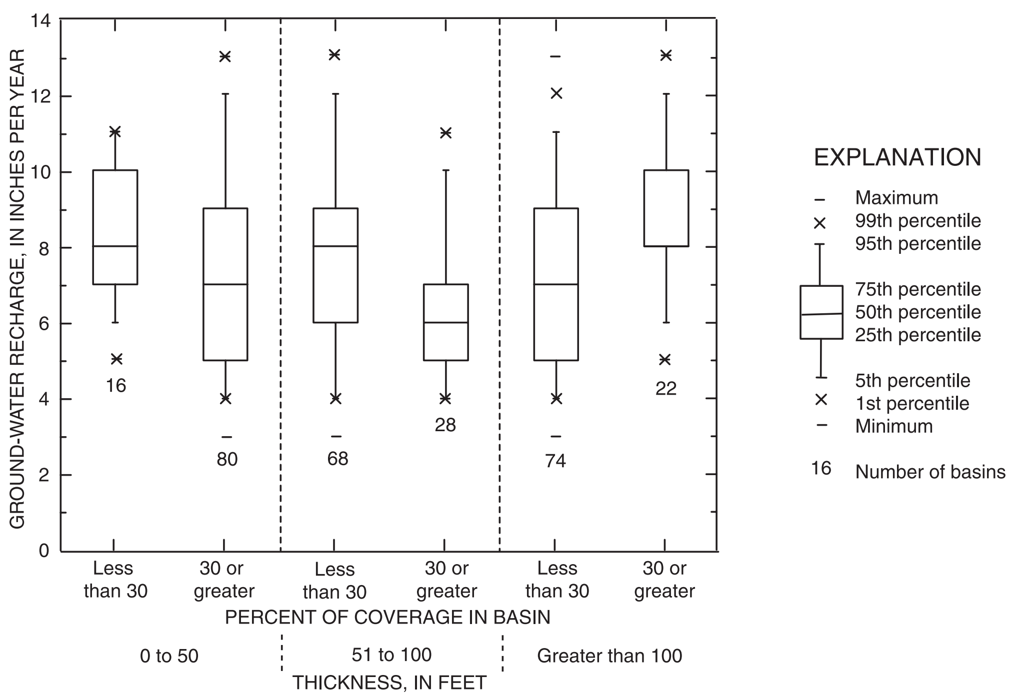

Figure 13. Relation between ground-water recharge estimates and glacial-sediment thickness characteristics for long-term continuous-record (LTCR) stations in Ohio.

more than 8 in/yr. However, the relation between thick glacial deposits and higher recharge may not be meaningful because the recharge estimate also can be explained for many of these basins by other factors, such as precipitation rates and basin coverage of high soil infiltration rates and coarse glacial deposits. Glacial thickness alone does not seem to be an important factor in ground-water recharge rates.

Six basins (13, 68, 180, 184, 253, 291) with at least 30 percent coverage of deposits at least 100 ft thick show the difficulty in correlating thickness with recharge and the other factors involved. Five of these basins (13, 68, 180, 184, 291) have ground-water recharge estimates of less than 7 in/yr. These five basins all have low percentages of soils with high infiltration rates and coarse glacial deposits; three have relatively low precipitation rates (13, 68, 291). Of these five basins, 291 has the highest percentage of coarse deposits (10 percent) but also has the lowest precipitation rate (34.0 in/yr). The sixth basin, the Mad River at Zanesfield (253), is an anomaly in that the recharge estimate of 10 in/yr is fairly high, but the basin has a low precipitation rate (35.7 in/yr), no soils with high infiltration rates, and less than 10 percent coarse glacial deposits. As noted earlier, the Mad River is known to have an unusually large base-flow component and probably is a regional discharge area (Koltun, 1995; Sheets and Yost, 1994). It is quite possible that some of the assumptions for using the RORA/RECESS programs are violated in this basin.

Physiography. The physiography of the basin, in terms of topographic relief, also was investigated as a potential factor in estimating the recharge rate. The Till and Eastern Lake Plains physiographic sections were combined into a “low relief” category and compared to the Southern New York and Kanawha physiographic sections (“moderate-high relief”). Aside from a very general pattern that the highest recharge estimates occur in regions of higher relief and the lowest recharge with lower relief, there is no clear relation between relief and recharge (fig. 14). The difficulty with this approach of using the physiographic sections to assess the relief in a basin is that the categories are very broad in terms of both the definition of the region and the characterization of relief.

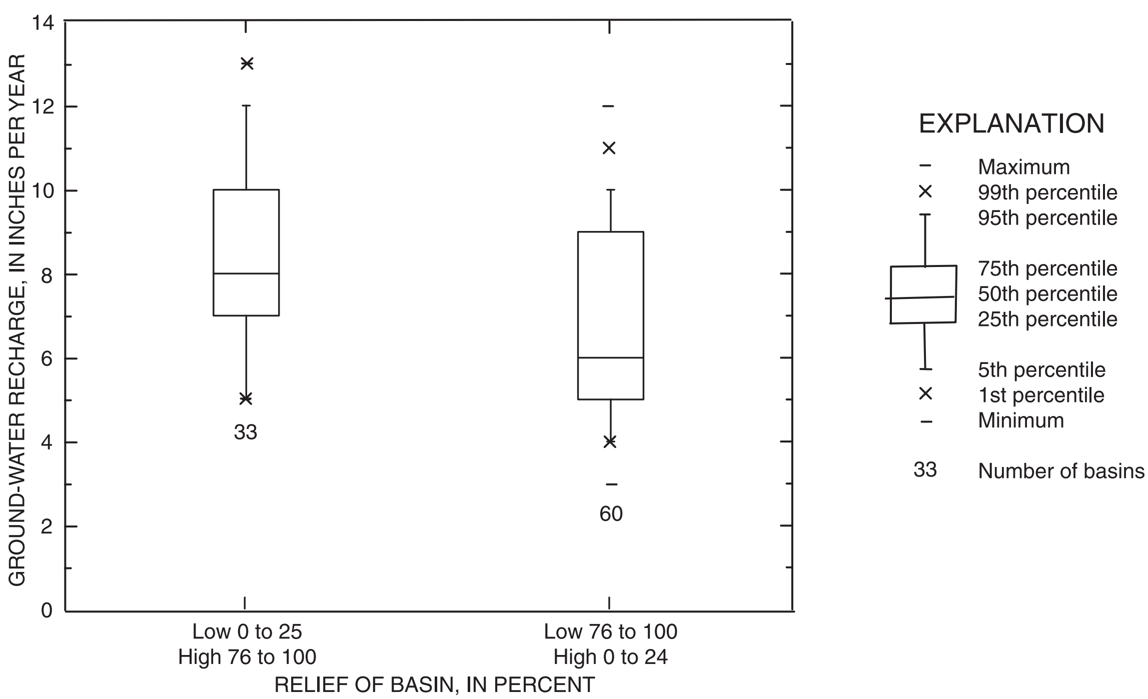

Figure 14. Relation between ground-water recharge estimates and physiography for the long-term continuous-record (LTCR) stations in Ohio.

Summary of relations between basin characteristics and recharge estimates. The boxplots for the 96 LTCR stations (figs. 10-13) indicate some general relations between precipitation, soil infiltration rates, glacial geology, and ground-water-recharge estimates. Physiography, or relief, may affect ground-water recharge, but the physiographic sections are not detailed enough surrogates to reveal any patterns. The table below is one way to summarize the general relations observed between basin characteristics and estimated ground-water recharge rates.

Although difficult to verify, particularly with limited examples for some cases, certain characteristics appear to have more affect on recharge than others: after accounting for the precipitation rate, soil infiltration rates are the first characteristic to consider, followed by glacial geology. This sequence is not unexpected because these two characteristics are, by their very nature, expected to be highly correlated. The thickness of the glacial sediments also should be considered, although it seems less important than the other characteristics.

Another approach to estimating ground-water recharge rates on the basis of basin characteristics is to develop a regression tree. Regression-tree modeling is useful for finding structure and summarizing large multivariate data sets. Tree-based models use a set of predictor variables (in this case, the basin characteristics) and a single-response variable (in this case, a recharge estimate). Of various models, the following explanatory variables produced the best results: precipitation and percentages of glacial thickness, coarse-grained sediments, other sediments, and soil infiltration rates. The regression-tree model chosen had 11 terminal nodes, a residual mean deviance of 1.842, and a median and maximum residual of -0.06667 and 2.867, respectively. The resulting regression-tree model is shown in figure 15.

Basin characteristic		Estimated ground-water recharge
Precipitation	less than 36 in/yr	6 in/yr or less
	more than 40 in/yr	6 in/yr or more
Soil infiltration rates	very low, in more than 20 percent of the basin	5 in/yr or less
	high, in more than 20 percent of the basin	8 in/yr or more
Coarse-grained glacial sediments	in more than 10 percent of the basin	8 in/yr or more
	in more than 21 percent of the basin	9 in/yr or more
Glacial sediments, 100 ft thick or more	in more than 30 percent of the basin	8 in/yr or more

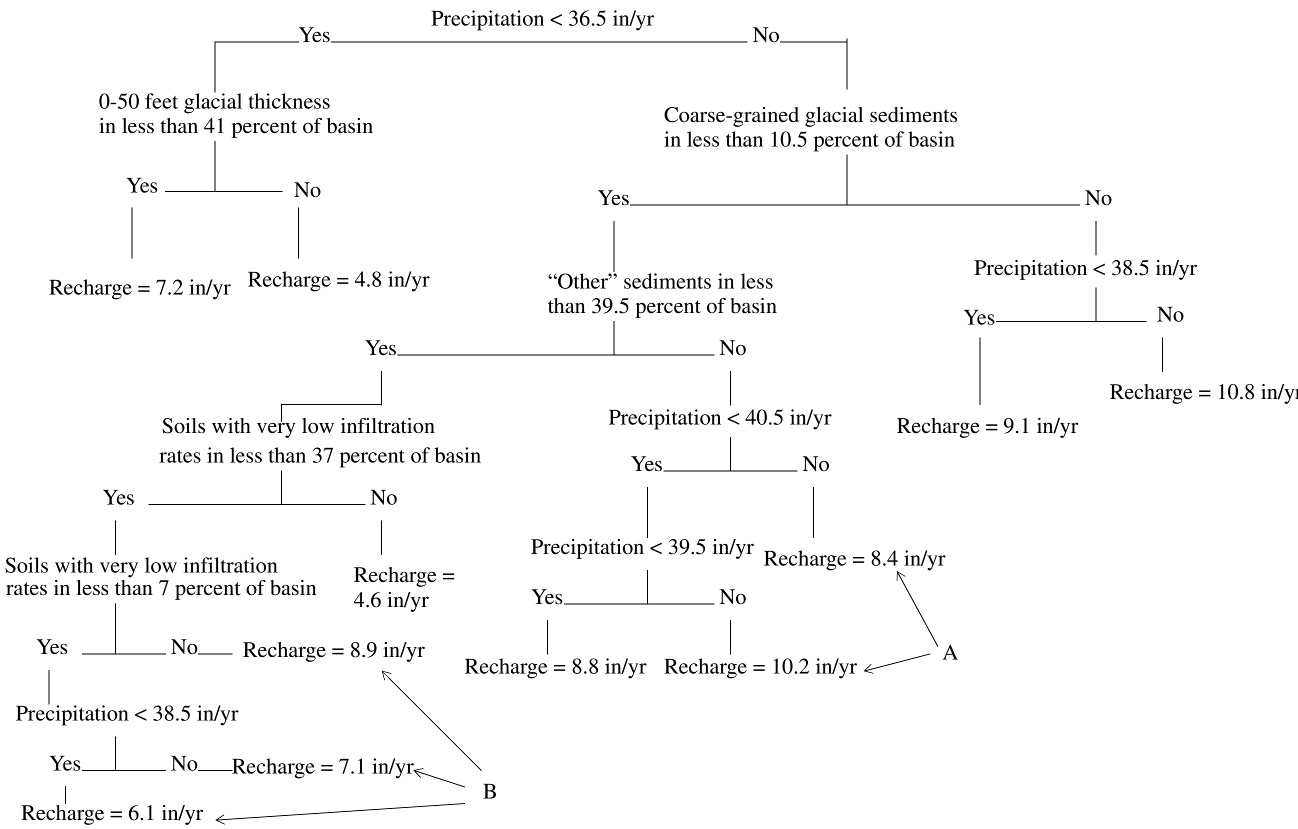

Figure 15. Regression-tree model results showing relation between basin characteristics and ground-water recharge estimates. (Inconsistencies noted by arrow sets A and B are discussed in the summary of the section titled "Relation of basin characteristics to ground-water recharge estimates." Recharge estimates are statistical output and are not intended to be predictive; see discussion in the same section and table 8.)

The regression-tree model produced a few results that appear inconsistent with the general patterns previously discussed. For example, the terminal nodes identified as "A" on figure 15 indicate a result where a basin with more precipitation has a recharge estimate that is less than the estimate for a basin with less precipitation. The "B" on figure 15 indicates a similar situation, where a basin with a greater percentage of soils with very low infiltration rate has a higher recharge estimate than a basin with a lower percentage of the same soils. These inconsistencies may indicate that some other unidentified factor may be acting as a surrogate for precipitation.

Short-term continuous-record (STCR) stations

Data from 30 streamflow-gaging stations without sufficient record for use with RORA were analyzed by PART in order to estimate the ground-water discharge and a MBI for each station. Like the LTCR stations, the STCR stations were located throughout Ohio. Drainage areas range from 1 to 644 mi^2; only one station had a drainage area greater than the recommended size of 500 mi^2 (table 5). Ground-water discharge estimates for the STCR stations range from 3 to 13 in/yr, with a median value of 5 in/yr. The MBI values range from 25.3 to 83.4, with a median of 36.2. Precipitation estimates for these 30 basins range from 33 to 41.5 in/yr, with a median of 36.9 in/yr (table 5). Most of the 30 basins are covered mainly with soils having moderate or low infiltration rates (table 6, at back of report). Six basins are at least 20 percent covered by soils with high infiltration rates, and five basins are at least 20 percent covered by soils with very low infiltration rates. Six basins have coarse-grained glacial sediments covering more than 10 percent of the basin; four of these have more than 21 percent coverage with coarse sediments (table 7, at back of report).

Table 5. Results of the PART program and precipitation estimates for short-term continuous-record (STCR) stations in Ohio

[mi^2, square miles; in/yr, inches per year]

Basin identifier (fig. 17)	Station name	Station number	Drainage area (mi^2)	Years of record used	Ground-water discharge (in/yr)	Mean base-flow index	Precipitation (in/yr)
2	Beech Creek near Bolton	03087000	17.4	1944-50	4	31.3	36.3
4	Deer Creek at Limaville	03088000	33.2	1942-50	5	38.1	35.5
15	Duck Creek at Leavittsburg	03093500	32.3	1942-47	3	28.6	35
91	Salt Fork near Cambridge	03142200	55.6	1957-66	5	41.8	40.5
101	Raccoon Creek at Grandville	03145500	82.7	1940-47	5	31.1	38
118	Clear Fork near Logan	03158000	14.8	1942-46	6	42.2	40
143	Symmes Creek at Getaway	03205500	335	1939-46	5	35.4	41.5
156	Whetstone Creek near Shawtown	03223500	61.8	1947-54	5	35	36.7
157	Shaw Creek at Shawtown	03224000	25.4	1947-54	5	35.4	36.5
170	Scioto Big Run at Briggsdale	03228000	11.0	1947-57	4	31.7	37.1
173	Alum Creek at Kilbourne	03228750	64.9	1971-80	5	36.5	37.3
194	Tar Hollow Creek at Tar Hollow State Park	03235500	1.35	1947-77	6	46.4	39
196	Little Salt Creek near Jackson	03236500	76.1	1926-31	5	37.7	41.3
203	Little Miami River near Selma	03239000	48.9	1953-57	5	61.3	38.3
204	North Fork Little Miami River near Pitchin	03239500	28.9	1953-57	5	72.1	38
209	Little Miami River at Spring Valley	03242000	361	1926-34[a] 1940-50	8	55.8	38.7
261	Buck Creek near New Moorefield	03267950	30.5	1968-75	11	83.4	37.5
262	East Fork Buck Creek near New Moorefield	03267960	28.7	1968-75	13	75.6	37.7
298	Eagle Creek near Findlay	04188500	55.0	1947-56	3	25.7	35
300	Blanchard River at Glandorf	04189500	644	1922-27[a] 1948-51	4	35.2	35
303	Town Creek near Van Wert	04191000	21.2	1946-52	4	25.3	36
311	North Branch of Portage River near Bowing Green	04195000	45.1	1924-31	7	50.2	33
317	Broken Sword Creek at Nevada	04196200	83.8	1977-80	6	37.4	36.3
322	Honey Creek near New Washington	04197020	17.0	1980-88	5	39.5	36.5
325	Wolf Creek at Bettsville	04197300	66.2	1977-80	4	32.2	34.5
326	East Branch Wolf Creek near Bettsville	04197450	82.4	1977-80	6	34.4	34.8
329	East Branch Huron River near Norwalk	04198500	85.5	1924-34	4	35.8	35.8
335	East Branch of Black River at Elyria	04200000	217	1923-30	4	26.4	35.3
365	Grand River near North Bristol	04209500	85.4	1943-46	5	33.2	38.8
367	Grand River near Rome	04210500	251	1943-46	6	39.9	40.5

[a] Weighted averages are reported for discharge and mean base-flow index because of the multiple periods of record.

Because of the shorter period of record for the STCR stations, RORA was not used to directly estimate ground-water recharge rates; thus, alternative approaches were needed. The PART-derived ground-water discharge rates and the recharge-discharge relation in figure 8 could not be used reliably for the STCR stations because short-term climatic variations can greatly alter the amount of recharge from year to year. The MBI, being a ratio of discharges, is much less affected by climatic variations and, therefore, was more useful in estimating recharge rates for these stations. Using the relations observed with the LTCR stations, ground-water recharge rates were estimated in three ways for the STCR stations.

The first method to estimate recharge (table 8) is a range based on the general observations of basin characteristics summarized in the previous section. Because no single characteristic is shown to predominate in affecting recharge rates, the characteristic-based recharge estimates were derived from a qualitative approach using the percentages of characteristics (tables 5, 6, and 7) and the observed relations, extra

Table 8. Ground-water recharge estimates for short-term continuous-record (STCR) stations in Ohio

[MBI, mean base-flow index]

Basin identifier (fig. 17)	Station name	Station number	MBI	Ground-water recharge estimate (inches per year)			
				Range, based on basin characterstics		MBI based	
				General observations[1]	Regression-tree model[2]	Range[3]	Value[4]
2	Beech Creek near Bolton	03087000	31.3	5-7	3-6	5-7	5
4	Deer Creek at Limaville	03088000	38.1	4-5	6-9	5-7	6
15	Duck Creek at Leavittsburg	03093500	28.6	5-8	3-6	4-5	4
91	Salt Fork near Cambridge	03142200	41.8	6-7	7-10	5-7	7
101	Raccoon Creek at Grandville	03145500	31.1	6-8	6-9	4-5	5
118	Clear Fork near Logan	03158000	42.2	7-9	9-12	7-8	7
143	Symmes Creek at Getaway	03205500	35.4	7-9	7-10	5-7	6
156	Whetstone Creek near Shawtown	03223500	35	6-8	5-8	5-7	6
157	Shaw Creek at Shawtown	03224000	35.4	5-7	6-8 or 5-8[5]	5-7	6
170	Scioto Big Run at Briggsdale	03228000	31.7	6-9	5-8	4-5	5
173	Alum Creek at Kilbourne	03228750	36.5	6-8	5-8	5-7	6
194	Tar Hollow Creek at Tar Hollow State Park	03235500	46.4	6-8	7-10	7-8	8
196	Little Salt Creek near Jackson	03236500	37.7	7-8	7-10	5-7	6
203	Little Miami River near Selma	03239000	61.3	7-9	8-11	9-10	11
204	North Fork Little Miami River near Pitchin	03239500	72.1	7-9	8-11	9-12	13
209	Little Miami River at Spring Valley	03242000	55.8	7-9	9-12	9-10	10
261	Buck Creek near New Moorefield	03267950	83.4	7-9	8-11	9-12	16
262	East Fork Buck Creek near New Moorefield	03267960	75.6	7-9	8-11	9-12	14
298	Eagle Creek near Findlay	04188500	25.7	4-5	3-6	4-5	4
300	Blanchard River at Glandorf	04189500	35.2	4-5	3-6	5-7	6
303	Town Creek near Van Wert	04191000	25.3	5-7	6-9	4-5	4
311	North Branch of Portage River near Bowing Green	04195000	50.2	5-7	6-9	7-8	9
317	Broken Sword Creek at Nevada	04196200	37.4	5-7	6-9	5-7	6
322	Honey Creek near New Washington	04197020	39.5	5-7	6-9 or 5-8[5]	5-7	7
325	Wolf Creek at Bettsville	04197300	32.2	4-6	3-6	4-5	5
326	East Branch Wolf Creek near Bettsville	04197450	34.4	4-5	3-6	5-7	5
329	East Branch Huron River near Norwalk	04198500	35.8	4-5	3-6	5-7	6
335	East Branch of Black River at Elyria	04200000	26.4	5-7	3-6	4-5	4
365	Grand River near North Bristol	04209500	33.2	6-8	3-6	5-7	5
367	Grand River near Rome	04210500	39.9	6-8	7-10	5-7	7

[1] Range is based on general observations discussed on pages 24-26.

[2] Range is based on rounding +/-1.5 of the finite value determined from the regression-tree model shown in figure 15.

[3] Range is based on the 25-75 percent interquartile range in figure 16.

[4] Value was calculated from the regression equation shown in figure 9A.

[5] Two ranges are given because two paths could be used on the regression tree.

weight being given to the precipitation and soil-infiltration characteristics. For example, in basin 2, the precipitation is 36.3 in/yr, which correlates with a recharge of 6 in/yr or less; glacial deposits 100 ft thick or more cover 57 percent of the basin, correlating with a recharge of 8 in/yr or more. However, because precipitation seems to be the more important characteristic, the characteristic-based recharge range listed in table 8 is 5 to 7 in/yr. In basin 203, the precipitation is 38.3 in/yr, which correlates with an estimated recharge between 7 and 9 in/yr (fig.10); coarse-grained glacial deposits cover 14 percent of the basin, correlating with a recharge of 8 in/yr or more; glacial deposits 100 ft thick or more cover 72 percent of the basin, correlating with a recharge of 8 in/yr or more; in light of all these relations, the characteristic-based recharge range is from 7 to 9 in/yr (table 8). In basin 325, the precipitation is 34.5 in/yr, giving a recharge estimate of 6 in/yr or less; very low infiltrating soils cover 48 percent of the basin correlating with a recharge estimate of 5 in/yr or less; thus, the low precipitation rate and very low infiltration soils, both important characteristics, result in a characteristic-based recharge range of 4 to 6 in/yr (table 8,.

The second method to estimate ground-water recharge for the STCR stations used the basin characteristics and the regression tree in figure 15. For each basin, the data in tables 5, 6, and 7 were used with the tree to obtain a finite recharge estimate. However, given the variability of conditions across the state, a range of values is probably more reasonable than a finite number. To get a range of values, 1.5 was added and subtracted from the results of the tree model, and each end of the range then was rounded to the nearest whole number—thus, a finite estimate of 4.8 in/yr from the tree becomes the range of 3 to 6 in/yr. Despite the inconsistencies noted earlier with the tree model, the ranges derived from this model are similar to those from the first method (table 8). It should be noted that two of the STCR stations (156 and 322) have two ranges for the regression-tree based estimates. These multiple ranges are published because the basins have a precipitation rate of 36.5 in/yr and, therefore, could go in either direction at the top of the tree (fig. 15).

The basin characteristic-recharge relations are qualitative and fairly general. So, in an effort to assess the reliability of characteristic-based estimates, a third method of estimating recharge was tried. As indicated in figure 9A, the MBI value correlates somewhat with the RORA-derived ground-water-recharge estimate for the LTCR stations. So, the third method estimates recharge for the STCR stations on the basis of the MBI values. MBI-based recharge rates were estimated as both a range and a single value. Using data from the LTCR stations, box plots of recharge estimates and MBI were prepared (fig. 16). The MBI-based estimate ranges listed in table 8 were derived from the 25 to 75 percent interquartile ranges on figure 16. The single-value recharge estimate was calculated from the MBI-recharge regression equation shown in figure 9A.

The three methods of estimating recharge rates for the STCR stations are in reasonable agreement. At least 2 of the 3 recharge ranges overlap for all the stations, and all 3 ranges overlap for 25 of the 30 stations (table 8). The recharge estimate calculated from the MBI value is 2 in/yr or more different from one of the characteristic ranges at four stations, and for both characteristic ranges at three stations. Although

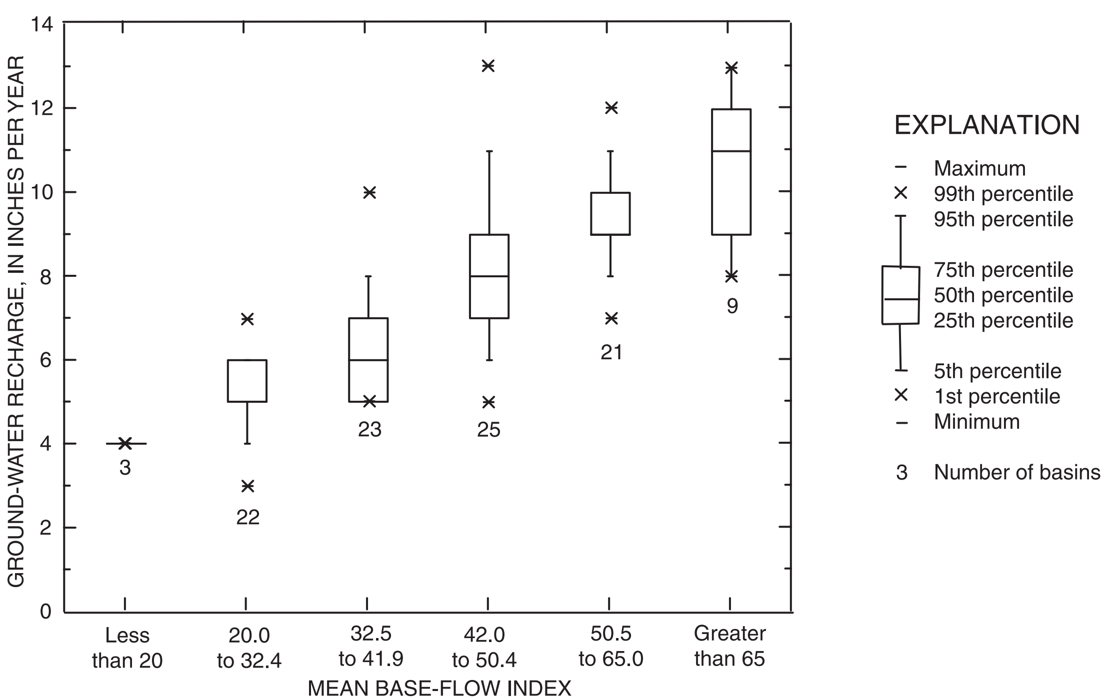

Figure 16. Relation between mean base-flow index MBI) and ground-water recharge for the long-term continuous record (LTCR) stations in Ohio.

recharge only weakly correlates with MBI (fig. 9A), the MBI-based estimation method may be the preferred method because this method is more quantitative than the basin-characteristic methods. If daily streamflow data are unavailable, however, the basin characteristics appear to provide reasonable estimates of ground-water recharge. The locations of the STCR stations with the MBI-based recharge estimate are shown in figure 17.

An additional 33 STCR stations were added at the end of the project. Basin characteristics were not determined for these additional stations. Ground-water recharge rates were estimated for these 33 stations on the basis of MBI values only. These data are presented in appendix B.

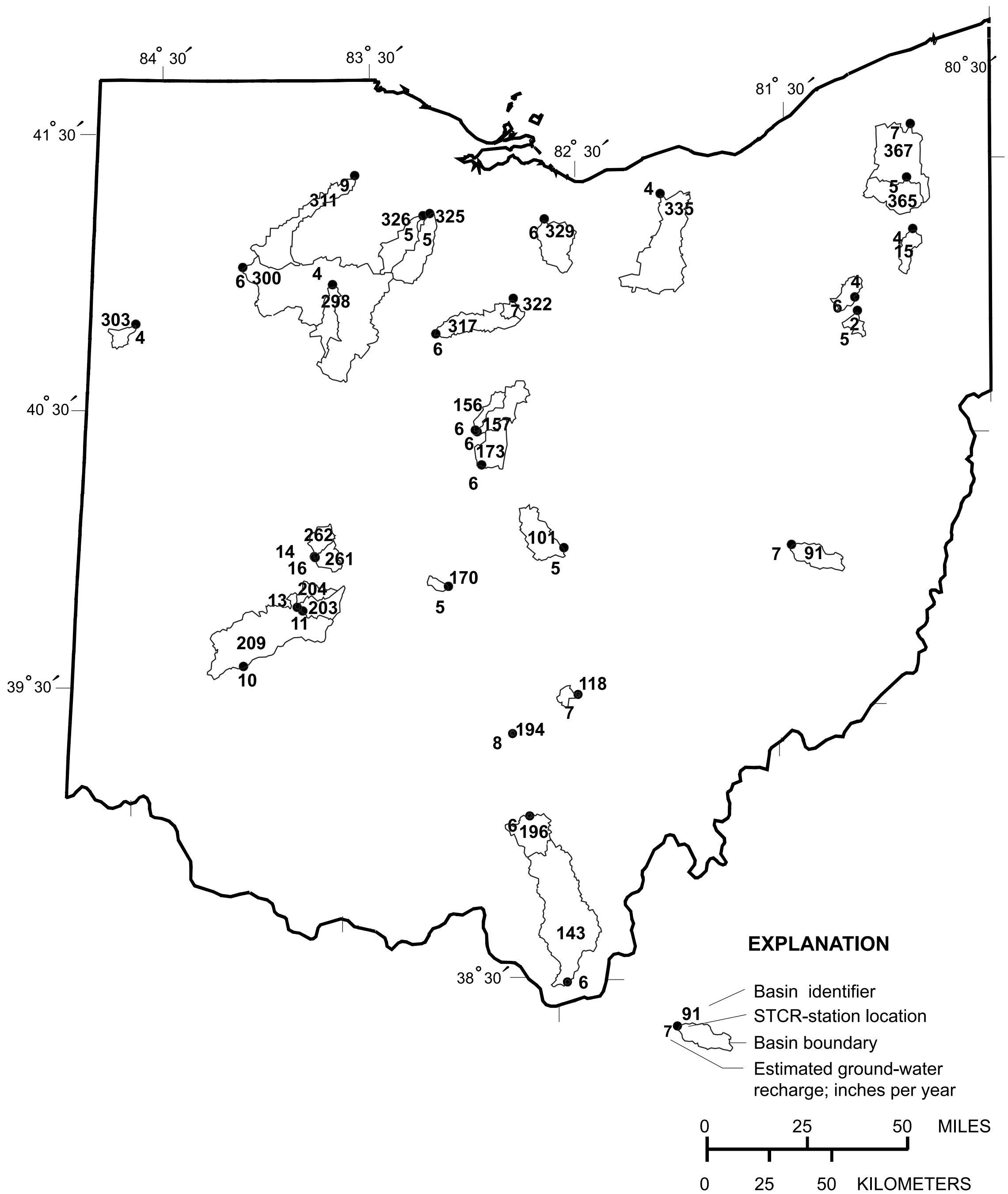

Figure 17. Distribution and estimates of ground-water recharge for short-term continuous-record (STCR) stations in Ohio.

Estimating ground-water recharge rates in basins without daily streamflow records

Although the PART program can be used for stations with only a few years of daily streamflow records, no comparable program is available for use with LFPR (low-flow partial-record) stations. Therefore, basin characteristics were determined for 28 basins with LFPR stations (tables 9 and 10, at back of report). Precipitation estimates for these 28 basins range from 35.7 to 43.2 in/yr, with a median of 37.9 in/yr. Most of the 28 basins are covered mainly with moderate- or low-infiltration-rate soils. Soils with high infiltration rates cover at least 20 percent of five of these basins, and soils with very low infiltration rates cover at least 20 percent of only one basin. In five basins, coarse-grained glacial deposits cover more than 10 percent of the basin; there are no basins with more than 20 percent coverage by coarse sediments.

In addition to estimating ground-water recharge rates by basin characteristics, various approaches were tried to find a relation that would allow recharge to be estimated from a low-flow statistic available for these partial-record stations. On the basis of data from the LTCR stations, there is a close relation between the MBI and the 90-percent duration flow divided by the mean annual flow (fig. 18). Using this relation, an MBI was calculated for the 28 LFPR sites, and the ground-water recharge rate was calculated from this MBI in the same way as for the STCR stations.

Estimates of the recharge rate determined from basin characteristics and the MBI relations are listed in table 11, as are the RORA-derived recharge rates for the LTCR index stations. The three ranges are comparable, although the overlap between the ranges is less than was seen with the STCR stations—all 3 ranges overlap for only 19 of the 28 stations. The MBI-calculated value of recharge is 2 in/yr or more different from one of the characteristic-based ranges at eight stations and for both characteristic ranges at three stations.

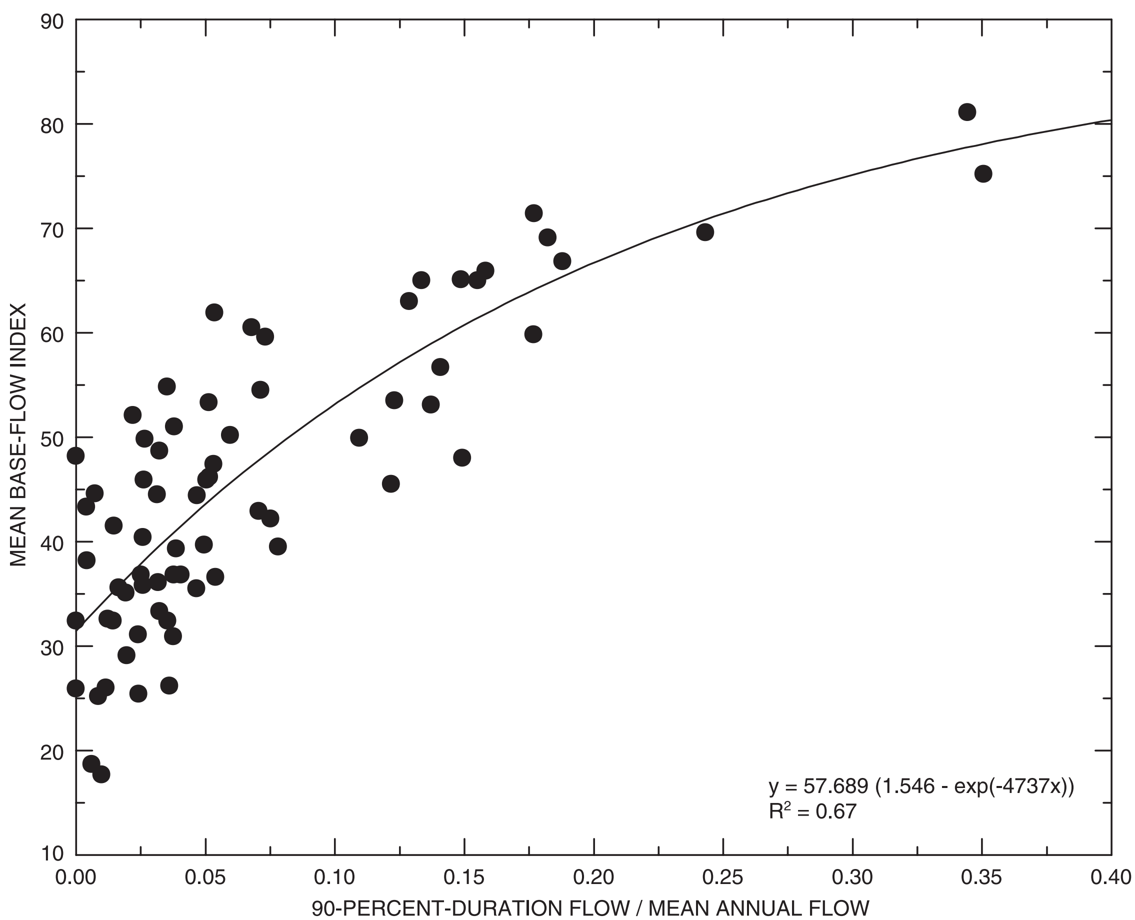

Figure 18. Relation between the 90-percent-duration flow divided by the mean annual flow and the mean base-flow index (MBI) for streams in Ohio.

Table 11. Ground-water recharge estimates for low-flow partial-record (LFPR) stations in Ohio

[mi^2, square miles; ft^3/s, cubic feet per second; in/yr, inches per year]

Basin identifier	Station name (index station basin identifier)	Station number	Drainage area (mi^2)	90-percent flow duration (ft^3/s)	Calculated mean base-flow index[1]	Ground-water recharge estimate (in/yr): Range, based on basin characterstics: General observations[2]	Range, based on basin characterstics: Regression-tree model[3]	MBI based: Calculated[4]	MBI based: Range[5]	Index station[6]
605	Hugle Run at Malvern (48)	03117280	21.3	1.9	51.4	8-10	8-11	9	9-10	10
606	Little Sandy Creek near Robertsville (48)	03117450	29.7	4.2	59.7	8-10	8-11	11	9-10	10
608	Apple Creek at Wooster (83)	03138820	33.7	4.5	58.6	4-5	3-6	11	9-10	9
609	Salt Creek at Holmesville (83)	03138910	42.6	1.5	40.4	4-5	3-6 or 5-8	7	5-7	9
611	Hocking River at Union Street at Lancaster (117)	03155895	36.2	4.0	55.0	8-10	8-11	10	9-10	7
612	Center Branch Rush Creek near Junction City (117)	03156549	24.9	.6	37.7	7-9	9-12	6	5-7	7
613	Rush Creek near Junction City (117)	03156550	71.0	3.4	43.2	8-10	9-12	7	7-8	7
614	Clear Creek at Clearport (116)	03156900	47.3	5.2	55.0	7-9	7-10	10	9-10	9
615	West Branch Shade River at Chester (125)	03159536	71.1	2.8	41.3	7-9	7-10	7	5-7	7
616	Middle Branch Shade River at Chester (125)	03159538	57.5	2.1	40.7	7-9	9-12 or 7-10	7	5-7	7
617	Campaign Creek near Gallipolis (142)	03160105	35.5	.3	33.8	7-9	7-10	5	5-7	8
618	Ice Creek at Ironton (142)	03216050	37.2	.5	35.1	8-10	7-10	6	5-7	8
619	Fulton Creek near Radnor (151)	03219520	46.9	.3	33.2	4-5	3-6	5	5-7	4
620	Bokes Creek near Warrensburg (151)	03219590	83.2	.1	31.8	4-5	3-6	5	4-5	4
621	Mill Creek near Broadway (151)	03219770	66.1	1.1	35.9	3-5	6-9	6	4-5	4
622	Mud Run near Caledonia (155)	03222700	16.1	.4	37.9	4-5	6-9	6	5-7	6
623	Flat Run near Caledonia (155)	03222800	29.9	.6	36.7	4-5	3-6	6	5-7	6
624	Blacklick Creek near Brice (103)	03228690	51.6	5.4	54.1	7-8	5-8	10	9-10	8
625	Walnut Creek near Carroll (103)	03229750	69.2	2.5	40.6	7-8	7-10	7	5-7	8
626	Walnut Creek near Groveport (117)	03229770	198	18.4	52.1	7-8	5-8	9	9-10	7
627	Big Darby Creek near West Jefferson (180)	03230230	239	7.4	39.4	7-8	7-10	6	5-7	6
628	Little Darby Creek near Irwin (180)	03230250	29.4	4	58.9	8-9	8-11	11	9-10	6
629	Little Darby Creek at West Jefferson (180)	03230310	162	5.1	39.5	7-8	5-8	7	5-7	6
630	Sugar Creek near Rock Mills (186)	03231800	78.3	.5	33.2	7-8	6-9	5	5-7	7
631	Clear Creek near Hillsboro (186)	03232480	35.4	2.8	49.6	8-10	9-12	9	7-8	7
632	Salt Creek at Adelphi (117)	03235090	47.8	1.2	38.0	7-8	7-10	6	5-7	7
641	Paramour Creek near Leesville (316)	04195950	27.2	1.2	42.4	4-5	3-6 or 5-8	7	7-8	6
642	Sandusky River near North Robinson (316)	04195970	39.7	1.6	40.4	4-5	3-6 or 5-8	7	5-7	6

[1] Mean base-flow index was calculated using the regression equation shown in figure 18; mean annual flow for these stations was determined from the equation $x = 1.002\ (\text{drainage area, in square miles})^{0.99879}$ (M.T. Whitehead and G.F. Koltun, U.S. Geological Survey, oral commun., 2001).

[2] Range is based on observations discussed on pages 24-26.

[3] Range is based on rounding +/- 1.5 of the finite value determined from the regression-tree model shown in figure 15.

[4] Value was calculated using the calculated mean base-flow index and the regression equation shown in figure 9A.

[5] Value is based on the 25-75 interquartile range in figure 16.

[6] Recharge rate listed is for the index station and was derived from RORA; see table 1.

Uncertainties abound in all these estimates. As mentioned earlier, the basin-characteristic ranges are fairly generalized, so estimates based on the MBI are preferred for the STCR stations. However, for these LFPR stations, the MBI-based estimates have additional uncertainties in that the MBI itself is calculated. The RORA-derived estimate for the index station can provide some additional guidance in selecting a recharge estimate for these LFPR stations. For example, the basin-characteristic estimates are lower for basin 608 than both the index station and the MBI-based estimate, but the index-station estimate is comparable to the MBI-based estimate; therefore, the preferred recharge estimate should probably be within the MBI-based range. The situation is the opposite for basin 609 in that the index-station estimate is higher than all the other estimates; therefore, the index-station estimate should be disregarded.

In general, the MBI-based estimate probably is the best because it is more quantitative than the basin-characteristic estimates. But the MBI-based estimate may need to be adjusted slightly depending on the basin-characteristic ranges and the index-station estimate. For example, for basin 628, the estimated recharge should be lowered to 10 in/yr rather than kept at 11 in/yr; for basin 624, the estimated recharge should be lowered to 9 in/yr from 10 in/yr. The locations of the LFPR stations and the estimated recharge rates are shown in figure 19.

In summary, it appears that the ground-water recharge rate can be reasonably estimated in areas without daily discharge data. If some low-flow partial-streamflow records are available in the area, the 90-percent-flow-duration value can be used to calculate an MBI, which then is used to estimate the recharge rate; however, estimates from basin characteristics and the index station should be considered as well. If there are no discharge records, then general basin characteristics can provide a usable range of values for the ground-water recharge rate.

Suggestions for future studies

With glacial deposits covering most of Ohio, the effect of bedrock geology on recharge is most likely limited; however, with the statewide bedrock geology data available for this study it was difficult to assess any potential effect. Although only 13 basins in this study are completely unglaciated, there is potential for additional work on the effect of bedrock geology in these basins and possibly in other basins without long-term continuous streamflow record. Additionally, the method used in this study to examine the effects of topography was unsuccessful. Other methods to assess the effect of topography may reveal a relation with the ground-water recharge rate. Other possible factors affecting ground-water recharge that could be investigated include agricultural drainage tiles, land use and changes in land use, and the use of dry wells in urban areas for surficial drainage. Many of these possible factors, such as land use, might be more easily investigated with smaller scale studies, perhaps at the county or multicounty scale.

The data for the 28 partial-record stations used in the study were from Schwartz (1985). Since then, low-flow records have been collected on more than 30 additional stations in Ohio. The ground-water recharge rate could be estimated for these new basins by means of the basin-characteristics approach or estimated more quickly by means of the calculated-MBI approach. Additionally, the relation between the MBI and the 80-percent-duration flow may be stronger than was seen with the 90-percent-duration data used in this study. The 80-percent relation was not thoroughly investigated because the data were not readily available in Schwartz (1985); however, publication of the 80-percent flow data for both the original stations and the additional stations is planned (D. E. Straub, U.S. Geological Survey, oral commun., 2000).

Summary and conclusions

Ground-water recharge rates were estimated for selected basins throughout Ohio on the basis of historical streamflow records. Three computer programs, RECESS, RORA, and PART, were used to develop estimates of the recession index, ground-water recharge and discharge, and the MBI (mean base-flow index, the ratio of mean base flow to mean streamflow). There were 103 stations with long-term continuous daily streamflow records (referred to as the LTCR stations) that met the requirements of the programs. Relations between the estimates of ground-water recharge and the MBI were examined. Estimates of the ground-water recharge rates for the LTCR stations ranged from 3 to 13 in/yr, with a median of 7 in/yr.

The basin characteristics of precipitation, soil-infiltration rates, glacial and bedrock geology, and physiography were investigated to determine whether ground-water recharge rates could be estimated in basins without long-term continuous streamflow records. Basin characteristics were determined from statewide data and a geographic information system (GIS). Although no discernible relation was found between recharge and the bedrock geology or physiography, relations with the other characteristics were seen. Basins with precipitation rates of less than 36 in/yr tended to have recharge rates of 5 in/yr or less; basins with precipitation greater than 40 in/yr tended to have recharge rates of 7 in/yr or more. Basins with 20 percent or more coverage of soils with very low

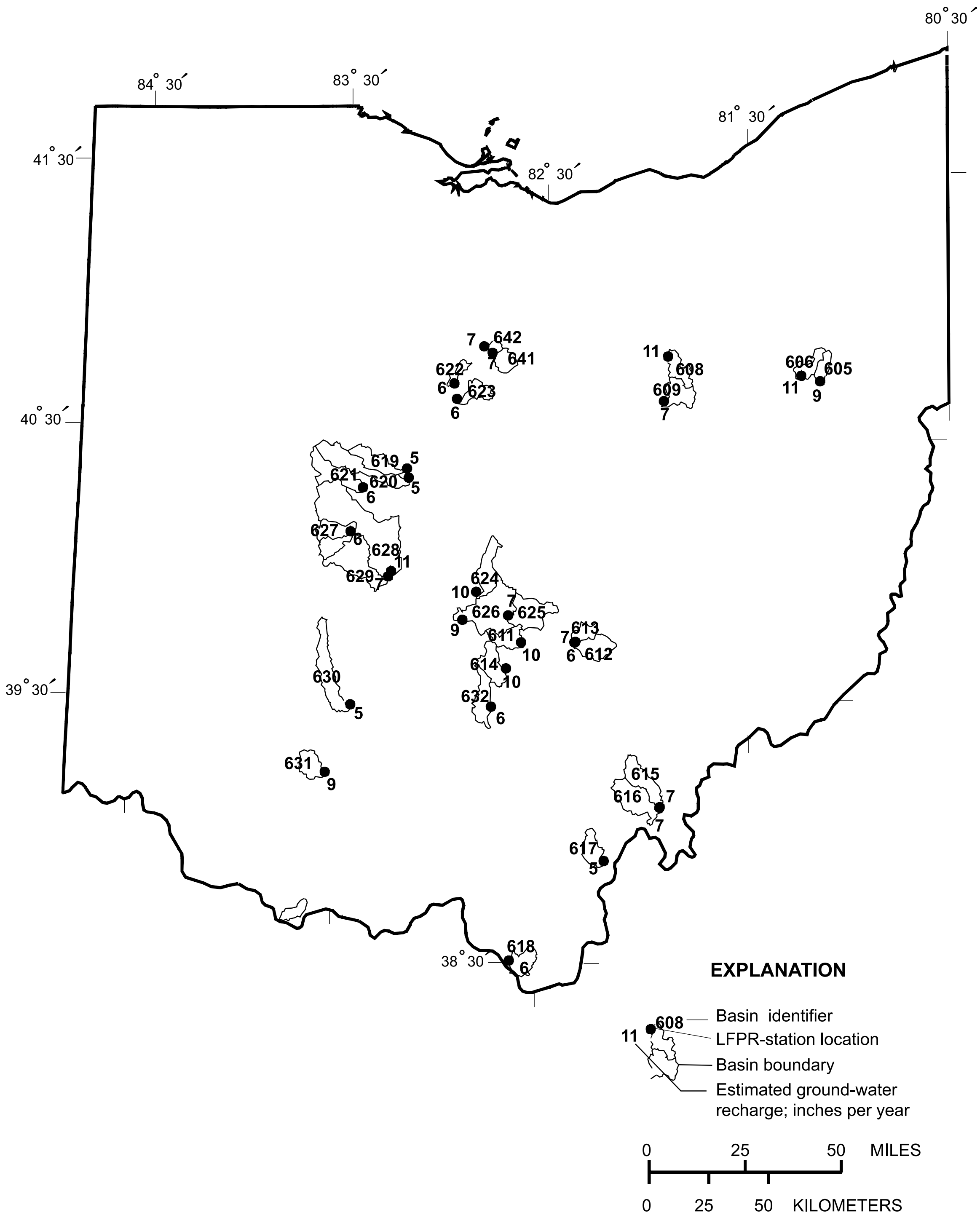

Figure 19. Distribution and estimates of ground-water recharge for low-flow partial-record (LFPR) stations in Ohio.

infiltration rates tended to have recharge rates of less than 7 in/yr; basins with 20 percent or more coverage of soils of high infiltration rates tended to have recharge rates of 8 in/yr or more. Basins with coarse glacial sediments covering more than 10 percent of the basin tended to have recharge rates of 8 in/yr or more; if coarse sediments covered more than 20 percent of the basin, the recharge rates increased to 9 in/yr or more.

Several methods of estimating ground-water recharge rates were tested for another 58 stations using the relations seen with the LTCR stations, basin characteristics, and low-flow statistics. For 30 stations with less than 10 years of daily streamflow record (referred to as STCR stations), the PART program was used to obtain MBI values. Recharge rates then were estimated in three ways on the basis of basin characteristics and the MBI. Recharge rates also were estimated for another 28 stations (referred to as LFPR stations) for which low-flow measurements were available but daily streamflow records were not. Estimates were made for these stations by means of basin characteristics and MBI values calculated from 90-percent-duration flow data.

Overall, if no streamflow records are available for a basin, then the ground-water recharge rate can be reasonably estimated by analyzing basin characteristics; however, the broad relations seen between the ground-water-recharge estimates and basin characteristics lend themselves to estimating ranges of values rather than a single recharge rate. Other relations seen in the data appear to provide alternative methods for estimating recharge rates not only for basins with limited daily streamflow records but also for basins with only a few low-flow measurements. Ground-water recharge estimates for Ohio, based on all 161 basins, range from 3 to 16 in/yr, with a median of 6 in/yr.

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Data tables

Table 2. Soil-infiltration-rate characterstics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing soil with					
		High infiltration rates	Moderate infiltration rates	Low infiltration rates	Very low infiltration rates	High plus moderate infiltration rates	Low plus very low infiltration rates
7	Mill Creek near Berlin Center	----	100	----	----	100	0
10	Kale Creek near Pricetown	----	----	34	66	0	100
11	West Branch Mahoning River near Ravenna	----	99	----	1	99	1
13	West Branch Mahoning River near Newton Falls	----	42	23	35	42	58
14	Eagle Creek at Phalanx Station	----	23	73	4	23	77
19	Mosquito Creek at Niles	----	29	71	----	29	71
26	Pymatuning Creek at Kinsman	----	46	54	----	46	54
27	Lisbon Creek at Lisbon	----	98	2	----	98	2
30	Yellow Creek near Hammondsville	32	36	33	----	68	33
31	Yellow Creek at Hammondsville	28	38	34	----	66	34
33	Short Creek near Dillonvale	----	100	----	----	100	0
34	Wheeling Creek below Blaine	8	92	----	----	100	0
37	Captina Creek at Armstrongs Mills	61	39	1	----	100	1
38	Little Muskingum River at Bloomfield	----	5	95	----	5	95
48	Sandy Creek at Waynesburg	16	71	12	----	87	12
51	Sandy Creek at Sandyville	12	82	7	----	94	7
59	Home Creek near New Philadelphia	16	82	3	----	98	3
68	Touby Run at Mansfield	----	100	----	----	100	0
74	Jerome Fork at Jeromeville	16	43	41	----	59	41
80	Kokosing River at Mount Vernon	15	39	45	----	54	45
81	Kokosing River at Millwood	11	56	34	----	67	34
83	Killbuck Creek at Killbuck	----	84	15	1	84	16
87	Mill Creek near Coshocton	----	78	22	----	78	22
96	Wakatomika Creek near Frazeysburg	----	100	----	----	100	0
102	North Fork Licking River at Utica	9	3	89	----	12	89
103	Licking River near Newark	11	13	72	5	24	77
104	Licking River at Toboso	9	23	64	4	32	68
108	Salt Creek near Chandlersville	----	91	9	----	91	9
116	Clear Creek at Rockbridge	29	18	43	11	47	54
117	Hocking River at Enterprise	25	41	31	3	66	34
125	Shade River at Chester	----	2	97	----	2	97
131	Sandy Run near Lake Hope	100	----	----	----	100	0
134	Big Four Hollow near Lake Hope	100	----	----	----	100	0
142	Raccoon Creek at Adamsville	35	59	5	----	94	5
144	Scioto River at LaRue	1	----	87	12	1	99
145	Little Scioto River above Marion	----	----	100	----	0	100
148	Scioto River near Prospect	----	3	88	9	3	97
149	Bokes Creek near Warrensburg	----	----	100	----	0	100
151	Mill Creek near Bellepoint	----	2	75	24	2	99
155	Olentangy River at Claridon	----	1	99	----	1	99
158	Whetstone Creek near Ashley	----	----	100	----	0	100
159	Olentangy River near Delaware	----	----	100	----	0	100
161	Olentangy River at Stratford	----	----	100	----	0	100
172	Big Walnut Creek at Central College	----	15	83	2	15	85
174	Alum Creek at Africa	----	21	79	----	21	79
175	Alum Creek at Columbus	----	20	80	----	20	80
176	Big Walnut Creek at Rees	----	17	82	1	17	83
180	Big Darby Creek at Darbyville	4	1	89	6	5	95
182	Deer Creek at Mount Sterling	----	----	100	----	0	100

Table 2. Soil-infiltration-rate characterstics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing soil with					
		High infiltration rates	Moderate infiltration rates	Low infiltration rates	Very low infiltration rates	High plus moderate infiltration rates	Low plus very low infiltration rates
184	Deer Creek at Williamsport	1	----	99	----	1	99
186	Paint Creek near Greenfield	15	----	85	----	15	85
187	Rattlesnake Creek at Centerfield	5	6	86	3	11	89
189	Rocky Fork near Barretts Mills	3	91	5	1	94	6
193	Salt Creek at Tarlton	----	----	100	----	0	100
195	Salt Creek near Londonderry	36	45	16	2	81	18
200	Upper Twin Creek at McGaw	----	100	----	----	100	0
201	Ohio Brush Creek near West Union	3	91	3	3	94	6
202	White Oak Creek near Georgetown	----	1	45	54	1	99
205	Little Miami River near Oldtown	23	3	66	8	26	74
206	North Fork Massie Creek at Cedarville	3	----	80	18	3	98
207	South Fork Massie Creek near Cedarville	----	----	80	20	0	100
208	Massie Creek at Wilberforce	21	----	66	13	21	79
210	Little Miami near Spring Valley	42	7	45	5	49	50
212	Anderson Fork near Burlington	20	----	73	8	20	81
213	Caesar Creek at Harveysburg	37	4	57	3	41	60
215	Little Miami River near Fort Ancient	41	4	48	6	45	54
221	East Fork Little Miami River near Marathon	11	3	31	56	14	87
222	East Fork Little Miami River at Williamsburg	9	2	27	62	11	89
224	East Fork Little Miami River near Batavia	6	4	30	60	10	90
226	East Fork Little Miami River at Perintown	4	7	30	59	11	89
238	Bokengehalas Creek near DeGraff	----	96	4	1	96	5
240	Stony Creek near DeGraff	----	61	39	----	61	39
253	Mad River at Zanesfield	----	30	71	----	30	71
255	Mad River at Urbana	----	50	50	1	50	51
263	Buck Creek at New Moorfield	23	22	54	----	45	54
264	Beaver Creek near Springfield	16	34	50	----	50	50
270	Wolf Creek at Trotwood	----	----	100	----	0	100
271	Wolf Creek at Dayton	2	----	98	----	2	98
274	Twin Creek near Ingomar	----	4	96	----	4	96
277	Sevenmile Creek at Camden	----	3	97	----	3	97
278	Sevenmile Creek at Collinsville	6	8	85	----	14	85
280	Fourmile Creek near Hamilton	----	49	51	----	49	51
291	Unnamed Tributary to Lost Creek near Farmer	----	----	100	----	0	100
299	Blanchard River near Findlay	----	----	95	5	0	100
312	Portage River at Woodville	4	----	16	80	4	96
316	Sandusky River near Bucyrus	----	7	94	----	7	94
318	Sandusky River near Upper Sandusky	----	7	91	2	7	93
323	Honey Creek at Melmore	3	----	92	5	3	97
324	Rock Creek at Tiffin	12	----	88	----	12	88
330	Huron River at Milan	7	3	87	3	10	90
333	Vermilion River near Vermilion	----	2	88	11	2	99
358	Tinkers Creek at Bedford	----	11	89	----	11	89
366	Phelps Creek near Windsor	----	----	99	1	0	100
368	Rock Creek near Rock Creek	----	----	94	6	0	100
370	Grand River near Madison	----	2	78	20	2	98
371	Grand River near Painesville	1	9	73	16	10	89

Table 3. Glacial-geology and sediment-thickness characterstics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing					Percentage of basin thickness				
		Coarse-grained sediments	Fine-grained sediments	Till	Patchy Quaternary	Other	0–50 feet	51–100 feet	101–200 feet	201–400 feet	Greater than 400 feet
7	Mill Creek near Berlin Center	11	----	89	----	----	70	4	19	7	----
10	Kale Creek near Pricetown	----	----	100	----	----	45	38	17	----	----
11	West Branch Mahoning River near Ravenna	18	----	82	----	----	61	33	7	----	----
13	West Branch Mahoning River near Newton Falls	5	----	95	----	----	40	27	24	10	----
14	Eagle Creek at Phalanx Station	18	----	82	----	----	57	26	14	3	----
19	Mosquito Creek at Niles[a]	8	----	92	----	----	75	22	2	----	----
26	Pymatuning Creek at Kinsman	19	----	81	----	----	90	10	----	----	----
27	Lisbon Creek at Lisbon	----	----	100	----	----	100	----	----	----	----
30	Yellow Creek near Hammondsville.	----	----	----	----	100	100	----	----	----	----
31	Yellow Creek at Hammondsville	----	----	----	----	100	100	----	----	----	----
33	Short Creek near Dillonvale	----	----	----	----	100	100	----	----	----	----
34	Wheeling Creek below Blaine	----	----	----	----	100	100	----	----	----	----
37	Captina Creek at Armstrongs Mills	----	----	----	----	100	100	----	----	----	----
38	Little Muskingum River at Bloomfield	----	----	----	----	100	100	----	----	----	----
48	Sandy Creek at Waynesburg	13	----	22	13	52	93	5	2	----	----
51	Sandy Creek at Sandyville	25	----	29	10	36	81	12	7	----	----
59	Home Creek near New Philadelphia	----	----	----	----	100	100	----	----	----	----
68	Touby Run at Mansfield	----	----	100	----	----	11	38	39	12	----
74	Jerome Fork at Jeromeville	15	----	85	----	----	67	16	15	3	----
80	Kokosing River at Mount Vernon	11	----	84	5	----	24	16	48	11	----
81	Kokosing River Millwood	11	----	55	33	1	50	10	29	10	----
83	Killbuck Creek at Killbuck	11	1	79	----	9	75	13	10	2	----
87	Mill Creek near Coshocton	----	----	----	----	100	100	----	----	----	----
96	Wakatomika Creek near Frazeysburg	3	3	4	43	48	99	1	----	----	----
102	North Fork Licking River at Utica	3	----	97	----	----	6	12	55	27	----
103	Licking River near Newark	10	3	85	2	----	13	16	45	24	1
104	Licking River at Toboso	10	3	70	12	6	28	14	37	20	1
108	Salt Creek near Chandlersville	----	----	----	----	100	100	----	----	----	----
116	Clear Creek at Rockbridge	4	11	51	24	11	99	1	----	----	----
117	Hocking River at Enterprise	7	11	32	25	25	92	4	4	----	----
125	Shade River at Chester	----	----	----	----	100	100	----	----	----	----
131	Sandy Run near Lake Hope	----	----	----	----	100	100	----	----	----	----
134	Big Four Hollow Lake Hope	----	----	----	----	100	100	----	----	----	----
142	Raccoon Creek Adamsville	----	----	----	----	100	100	----	----	----	----
144	Scioto River at LaRue	----	6	94	----	----	42	43	15	----	----
145	Little Scioto River above Marion	----	19	81	----	----	47	53	----	----	----
148	Scioto River near Prospect	----	12	88	----	----	54	38	8	----	----
149	Bokes Creek near Warrensburg	----	----	100	----	----	62	38	----	----	----
151	Mill Creek near Bellepoint	----	4	96	----	----	46	44	10	----	----
155	Olentangy River at Claridon	----	----	100	----	----	46	52	3	----	----
158	Whetstone Creek near Ashley	----	----	100	----	----	49	33	16	2	----
159	Olentangy River near Delaware	----	----	100	----	----	61	36	5	----	----
161	Olentangy River at Stratford	1	----	99	----	----	62	33	5	----	----
172	Big Walnut Creek at Central College	----	----	100	----	----	49	31	14	6	----
174	Alum Creek at Africa	2	----	98	----	----	72	22	6	----	----
175	Alum Creek at Columbus	3	----	97	----	----	52	25	21	2	----
176	Big Walnut Creek at Rees	3	----	97	----	----	51	25	20	4	----
180	Big Darby Creek at Darbyville	4	1	95	----	----	14	40	44	1	----
182	Deer Creek at Mount Sterling	4	----	96	----	----	10	90	----	----	----
184	Deer Creek at Williamsport	6	----	94	----	----	4	20	76	----	----

Table 3. Glacial-geology and sediment-thickness characterstics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing					Percentage of basin thickness				
		Coarse-grained sediments	Fine-grained sediments	Till	Patchy Quaternary	Other	0–50 feet	51–100 feet	101–200 feet	201–400 feet	Greater than 400 feet
186	Paint Creek near Greenfield	----	----	100	----	----	21	62	17	----	----
187	Rattlesnake Creek at Centerfield	2	----	98	----	----	82	14	4	----	----
189	Rocky Fork near Barretts Mills	36	----	17	47	----	100	----	----	----	----
193	Salt Creek at Tarlton	----	----	100	----	----	99	1	----	----	----
195	Salt Creek near Londonderry	10	3	16	11	60	94	2	4	----	----
200	Upper Twin Creek at McGaw	4	----	----	----	96	100	----	----	----	----
201	Ohio Brush Creek near West Union	5	2	6	57	31	98	1	1	----	----
202	White Oak Creek near Georgetown	3	----	93	5	----	97	3	----	----	----
205	Little Miami River near Oldtown	24	----	76	----	----	31	22	46	1	----
206	North Fork Massie Creek at Cedarville	3	----	97	----	----	54	17	29	----	----
207	South Fork Massie Creek near Cedarville	1	----	99	----	----	51	6	43	----	----
208	Massie Creek at Wilberforce	3	----	97	----	----	66	10	25	----	----
210	Little Miami River near Spring Valley	22	----	78	----	----	40	16	31	12	1
212	Anderson Fork near Burlington	1	----	99	----	----	64	4	30	2	----
213	Caesar Creek at Harveysburg	6	----	94	----	----	48	3	35	12	2
215	Little Miami River near Fort Ancient	15	1	83	----	----	48	12	29	11	1
221	East Fork Little Miami River near Marathon	5	----	93	2	----	82	1	17	----	----
222	East Fork Little Miami River at Williamsburg	4	----	94	2	----	85	1	14	----	----
224	East Fork Little Miami River near Batavia	5	----	93	2	----	90	1	9	----	----
226	East Fork Little Miami River at Perintown	4	----	93	3	----	92	1	7	----	----
238	Bokengehalas Creek near DeGraff	15	----	85	----	----	2	50	49	----	----
240	Stony Creek near DeGraff	28	----	72	----	----	1	2	97	----	----
253	Mad River at Zanesfield	6	----	94	----	----	6	58	36	----	----
255	Mad River at Urbana	61	----	39	----	----	14	30	55	2	----
263	Buck Creek at New Moorfield	44	2	54	----	----	4	19	77	----	----
264	Beaver Creek near Springfield	24	----	76	----	----	----	----	100	----	----
270	Wolf Creek at Trotwood	2	----	98	----	----	53	21	26	----	----
271	Wolf Creek at Dayton	5	----	95	----	----	68	17	13	2	----
274	Twin Creek near Ingomar	2	----	98	----	----	47	43	10	----	----
277	Sevenmile Creek at Camden	2	----	98	----	----	50	41	9	----	----
278	Sevenmile Creek at Collinsville	3	----	97	----	----	54	39	7	----	----
280	Fourmile Creek near Hamilton	6	----	93	----	----	54	38	7	----	----
291	Unnamed Tributary to Lost Creek near Farmer	10	----	90	----	----	----	----	60	40	----
299	Blanchard River near Findlay	----	11	89	----	----	76	22	2	----	----
312	Portage River at Woodville	----	----	100	----	----	72	26	2	----	----
316	Sandusky River near Bucyrus	----	20	80	----	----	65	34	1	----	----
318	Sandusky River near Upper Sandusky	----	17	83	----	----	39	60	2	----	----
323	Honey Creek at Melmore	----	11	88	----	1	47	50	3	----	----
324	Rock Creek at Tiffin	----	----	100	----	----	53	48	----	----	----
330	Huron River at Milan	----	4	95	----	----	67	28	4	----	----
333	Vermilion River near Vermilion	2	3	96	----	----	42	44	14	----	----
358	Tinkers Creek at Bedford	14	----	86	----	----	42	14	32	9	3
366	Phelps Creek near Windsor	----	----	100	----	----	78	23	----	----	----
368	Rock Creek near Rock Creek	7	----	93	----	----	89	9	1	----	----
370	Grand River near Madison	3	12	85	----	----	94	4	1	----	----
371	Grand River near Painesville	2	10	88	----	----	74	13	12	1	----

[a]Reservior in basin appears to interfere with the geographic information system data on glacial sediments; percentages of coarse-grained sediments may be slightly greater than reported.

Table 4. Physiographic charactersitics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing						
		Till Plains Section	Southern New York Section	Kanawha Section	Eastern Lake Plain Section	Lexington Plain Section	Low relief	Moderate to steep relief
7	Mill Creek near Berlin Center	----	100	----	----	----	0	100
10	Kale Creek near Pricetown	----	100	----	----	----	0	100
11	West Branch Mahoning River near Ravenna	----	100	----	----	----	0	100
13	West Branch Mahoning River near Newton Falls	----	100	----	----	----	0	100
14	Eagle Creek at Phalanx Station	----	100	----	----	----	0	100
19	Mosquito Creek at Niles	----	100	----	----	----	0	100
26	Pymatuning Creek at Kinsman	----	100	----	----	----	0	100
27	Lisbon Creek at Lisbon	----	----	100	----	----	0	100
30	Yellow Creek near Hammondsville	----	----	100	----	----	0	100
31	Yellow Creek at Hammondsville	----	----	100	----	----	0	100
33	Short Creek near Dillonvale	----	----	100	----	----	0	100
34	Wheeling Creek below Blaine	----	----	100	----	----	0	100
37	Captina Creek at Armstrongs Mills	----	----	100	----	----	0	100
38	Little Muskingum River at Bloomfield	----	----	100	----	----	0	100
48	Sandy Creek at Waynesburg	----	----	100	----	----	0	100
51	Sandy Creek at Sandyville	----	21	79	----	----	0	100
59	Home Creek near New Philadelphia	----	----	100	----	----	0	100
68	Touby Run at Mansfield	----	----	100	----	----	0	100
74	Jerome Fork at Jeromeville	17	83	----	----	----	17	83
80	Kokosing River at Mount Vernon	91	----	9	----	----	91	9
81	Kokosing River at Millwood	55	----	45	----	----	55	45
83	Killbuck Creek at Killbuck	----	42	58	----	----	0	100
87	Mill Creek near Coshocton	----	----	100	----	----	0	100
96	Wakatomika Creek near Frazeysburg	----	----	100	----	----	0	100
102	North Fork Licking River at Utica	84	----	16	----	----	84	16
103	Licking River near Newark	79	----	21	----	----	79	21
104	Licking River at Toboso	63	----	37	----	----	63	37
108	Salt Creek near Chandlersville	----	----	100	----	----	0	100
116	Clear Creek at Rockbridge	92	----	8	----	----	92	8
117	Hocking River at Enterprise	39	----	61	----	----	39	61
125	Shade River at Chester	----	----	100	----	----	0	100
131	Sandy Run near Lake Hope	----	----	100	----	----	0	100
134	Big Four Hollow near Lake Hope	----	----	100	----	----	0	100
142	Raccoon Creek at Adamsville	----	----	100	----	----	0	100
144	Scioto River at LaRue	100	----	----	----	----	100	0
145	Little Scioto River above Marion	100	----	----	----	----	100	0
148	Scioto River near Prospect	100	----	----	----	----	100	0
149	Bokes Creek near Warrensburg	100	----	----	----	----	100	0
151	Mill Creek near Bellepoint	100	----	----	----	----	100	0
155	Olentangy River at Claridon	100	----	----	----	----	100	0
158	Whetstone Creek near Ashley	100	----	----	----	----	100	0
159	Olentangy River near Delaware	100	----	----	----	----	100	0
161	Olentangy River at Stratford	100	----	----	----	----	100	0
172	Big Walnut Creek at Central College	100	----	----	----	----	100	0
174	Alum Creek at Africa	100	----	----	----	----	100	0
175	Alum Creek at Columbus	100	----	----	----	----	100	0
176	Big Walnut Creek at Rees	100	----	----	----	----	100	0
180	Big Darby Creek at Darbyville	100	----	----	----	----	100	0
182	Deer Creek at Mount Sterling	100	----	----	----	----	100	0
184	Deer Creek at Williamsport	100	----	----	----	----	100	0

Table 4. Physiographic charactersitics for long-term continuous-record (LTCR) stations in Ohio

Basin identifier (fig. 1)	Station name	Percentage of basin containing						
		Till Plains Section	Southern New York Section	Kanawha Section	Eastern Lake Plain Section	Lexington Plain Section	Low relief	Moderate to steep relief
186	Paint Creek near Greenfield	100	----	----	----	----	100	0
187	Rattlesnake Creek at Centerfield	100	----	----	----	----	100	0
189	Rocky Fork near Barretts Mills	100	----	----	----	----	100	0
193	Salt Creek at Tarlton	100	----	----	----	----	100	0
195	Salt Creek near Londonderry	18	----	82	----	----	18	82
200	Upper Twin Creek at McGaw	100	----	----	----	----	100	0
201	Ohio Brush Creek near West Union	47	----	1	----	52	47	1
202	White Oak Creek near Georgetown	100	----	----	----	----	100	0
205	Little Miami River near Oldtown	100	----	----	----	----	100	0
206	North Fork Massie Creek at Cedarville	100	----	----	----	----	100	0
207	South Fork Massie Creek near Cedarville	100	----	----	----	----	100	0
208	Massie Creek at Wilberforce	100	----	----	----	----	100	0
210	Little Miami near Spring Valley	100	----	----	----	----	100	0
212	Anderson Fork near Burlington	100	----	----	----	----	100	0
213	Caesar Creek at Harveysburg	100	----	----	----	----	100	0
215	Little Miami River near Fort Ancient	100	----	----	----	----	100	0
221	East Fork Little Miami River near Marathon	100	----	----	----	----	100	0
222	East Fork Little Miami River at Williamsburg	100	----	----	----	----	100	0
224	East Fork Little Miami River near Batavia	100	----	----	----	----	100	0
226	East Fork Little Miami River at Perintown	100	----	----	----	----	100	0
238	Bokengehalas Creek near DeGraff	100	----	----	----	----	100	0
240	Stony Creek near DeGraff	100	----	----	----	----	100	0
253	Mad River at Zanesfield	100	----	----	----	----	100	0
255	Mad River at Urbana	100	----	----	----	----	100	0
263	Buck Creek at New Moorfield	100	----	----	----	----	100	0
264	Beaver Creek near Springfield	100	----	----	----	----	100	0
270	Wolf Creek at Trotwood	100	----	----	----	----	100	0
271	Wolf Creek at Dayton	100	----	----	----	----	100	0
274	Twin Creek near Ingomar	100	----	----	----	----	100	0
277	Sevenmile Creek at Camden	100	----	----	----	----	100	0
278	Sevenmile Creek at Collinsville	100	----	----	----	----	100	0
280	Fourmile Creek near Hamilton	100	----	----	----	----	100	0
291	Unnamed Tributary to Lost Creek near Farmer	----	----	----	100	----	100	0
299	Blanchard River near Findlay	99	----	----	1	----	100	0
312	Portage River at Woodville	8	----	----	92	----	100	0
316	Sandusky River near Bucyrus	100	----	----	----	----	100	0
318	Sandusky River near Upper Sandusky	100	----	----	----	----	100	0
323	Honey Creek at Melmore	100	----	----	----	----	100	0
324	Rock Creek at Tiffin	100	----	----	----	----	100	0
330	Huron River at Milan	82	----	----	18	----	100	0
333	Vermilion River near Vermilion	100	----	----	----	----	100	0
358	Tinkers Creek at Bedford	----	100	----	----	----	0	100
366	Phelps Creek near Windsor	----	100	----	----	----	0	100
368	Rock Creek near Rock Creek	----	100	----	----	----	0	100
370	Grand River near Madison	----	100	----	----	----	0	100
371	Grand River near Painesville	----	97	----	3	----	3	97

Table 6. Soil-infiltration-rate characterstics for short-term continuous-record (STCR) stations in Ohio

Basin identifier (fig. 17)	Station name	Percentage of basin containing soil with					
		High infiltration rates	Moderate infiltration rates	Low infiltration rates	Very low infiltration rates	High plus moderate infiltration rates	Low plus very low infiltration rates
2	Beech Creek near Bolton	----	98	----	2	98	2
4	Deer Creek at Limaville	----	87	13	----	87	13
15	Duck Creek at Leavittsburg	----	24	75	1	24	76
91	Salt Fork near Cambridge	14	40	46	----	54	46
101	Raccoon Creek at Grandville	7	1	92	----	8	92
118	Clear Fork near Logan	83	17	----	----	100	0
143	Symmes Creek at Getaway	42	11	47	----	53	47
156	Whetstone Creek near Shawtown	----	----	100	----	0	100
157	Shaw Creek at Shawtown	----	----	100	----	0	100
170	Scioto Big Run at Briggsdale	----	----	100	----	0	100
173	Alum Creek at Kilbourne	----	7	93	----	7	93
194	Tar Hollow Creek at Tar Hollow State Park	----	100	----	----	100	0
196	Little Salt Creek near Jackson	38	62	----	----	100	0
203	Little Miami River near Selma	----	----	83	17	0	100
204	North Fork Little Miami River near Pitchin	30	15	55	----	45	55
209	Little Miami River at Spring Valley	41	8	45	5	49	50
261	Buck Creek near New Moorefield	26	13	61	----	39	61
262	East Fork Buck Creek near New Moorefield	18	24	59	----	42	59
298	Eagle Creek near Findlay	----	98	----	2	98	2
300	Blanchard River at Glandorf	----	----	92	8	0	100
303	Town Creek near Van Wert	----	----	100	----	0	100
311	North Branch of Portage River near Bowing Green	7	----	1	92	7	93
317	Broken Sword Creek at Nevada	----	8	92	----	8	92
322	Honey Creek near New Washington	----	----	100	----	0	100
325	Wolf Creek at Bettsville	7	----	44	48	7	92
326	East Branch Wolf Creek near Bettsville	2	25	60	14	27	74
329	East Branch Huron River near Norwalk	4	6	91	----	10	91
335	East Branch of Black River at Elyria	----	2	30	69	2	99
365	Grand River near North Bristol	----	21	26	53	21	79
367	Grand River near Rome	----	11	60	29	11	89

Table 7. Glacial-geology and sediment-thickness characterstics for short-term continuous-record (STCR) stations in Ohio

Basin identifier (fig. 17)	Station name	Percentage of basin containing					Percentage of basin thickness				
		Coarse-grained sediments	Fine-grained sediments	Till	Patchy Quaternary	Other	0–50 feet	51–100 feet	101–200 feet	201–400 feet	Greater than 400 feet
2	Beech Creek near Bolton	----	----	100	----	----	----	43	57	----	----
4	Deer Creek at Limaville	2	----	98	----	----	24	55	14	7	----
15	Duck Creek at Leavittsburg	18	----	82	----	----	70	17	13	----	----
91	Salt Fork near Cambridge	----	----	----	----	100	100	----	----	----	----
101	Raccoon Creek at Grandville	8	----	92	----	----	----	17	58	20	5
118	Clear Fork near Logan	6	----	----	----	94	100	----	----	----	----
143	Symmes Creek at Getaway	----	----	----	----	100	100	----	----	----	----
156	Whetstone Creek near Shawtown	----	----	100	----	----	34	42	21	3	----
157	Shaw Creek at Shawtown	----	----	100	----	----	69	23	8	----	----
170	Scioto Big Run at Briggsdale	----	----	100	----	----	----	50	42	9	----
173	Alum Creek at Kilbourne	----	----	100	----	----	69	27	4	----	----
194	Tar Hollow Creek at Tar Hollow State Park	----	----	----	----	100	100	----	----	----	----
196	Little Salt Creek near Jackson	----	2	----	----	98	100	----	----	----	----
203	Little Miami River near Selma	14	----	89	----	----	1	27	72	----	----
204	North Fork Little Miami River near Pitchin	41	----	59	----	----	5	35	61	----	----
209	Little Miami River at Spring Valley	22	----	78	----	----	40	17	31	11	1
261	Buck Creek near New Moorefield	39	4	57	----	----	3	24	73	----	----
262	East Fork Buck Creek near New Moorefield	42	2	56	----	----	2	14	85	----	----
298	Eagle Creek near Findlay	----	4	96	----	----	87	13	----	----	----
300	Blanchard River at Glandorf	1	7	92	----	----	78	20	2	----	----
303	Town Creek near Van Wert	----	----	100	----	----	22	42	36	1	----
311	North Branch of Portage River near Bowing Green	----	----	100	----	----	29	64	7	----	----
317	Broken Sword Creek at Nevada	----	7	93	----	----	25	73	1	----	----
322	Honey Creek near New Washington	----	44	56	----	----	26	66	8	----	----
325	Wolf Creek at Bettsville	----	----	100	----	----	92	8	----	----	----
326	East Branch Wolf Creek near Bettsville	3	----	97	----	----	61	38	1	----	----
329	East Branch Huron River near Norwalk	----	----	100	----	----	80	18	1	----	----
335	East Branch of Black River at Elyria	2	5	93	----	----	72	19	8	1	----
365	Grand River near North Bristol	2	4	93	----	----	51	22	22	5	----
367	Grand River near Rome	2	14	85	----	----	59	18	21	2	----

Table 9. Precipitation estimates and soil-infiltration-rate characteristics for low-flow partial-record (LFPR) stations in Ohio

[in/yr, inches per year]

Basin identifier (fig. 19)	Station name (index station basin identifier)	Station number	Precipitation (in/yr)	Percentage of basin containing soil with			
				High infiltration rates	Moderate infiltration rates	Low infiltration rates	Very low infiltration rates
605	Hugle Run at Malvern (48)	03117280	37.0	35	65	----	----
606	Little Sandy Creek near Robertsville (48)	03117450	37.0	23	77	----	----
608	Apple Creek at Wooster (83)	03138820	36.0	----	100	----	----
609	Salt Creek at Holmesville (83)	03138910	36.5	----	100	----	----
611	Hocking River at Union Street at Lancaster (117)	03155895	38.3	35	65	----	----
612	Center Branch Rush Creek near Junction City (117)	03156549	40.0	18	82	----	----
613	Rush Creek near Junction City (117)	03156550	39.8	56	44	----	----
614	Clear Creek at Clearport (116)	03156900	38.8	7	3	74	16
615	West Branch Shade River at Chester (125)	03159536	41.0	----	4	96	----
616	Middle Branch Shade River at Chester (125)	03159538	40.5	1	----	99	----
617	Campaign Creek near Gallipolis (142)	03160105	41.3	19	2	79	----
618	Ice Creek at Ironton (142)	03216050	42.2	59	----	41	----
619	Fulton Creek near Radnor (151)	03219520	35.7	----	----	100	----
620	Bokes Creek near Warrensburg (151)	03219590	35.7	----	----	100	----
621	Mill Creek near Broadway (151)	03219770	35.8	----	5	47	48
622	Mud Run near Caledonia (155)	03222700	35.8	----	----	100	----
623	Flat Run near Caledonia (155)	03222800	36.3	----	----	100	----
624	Blacklick Creek near Brice (103)	03228690	37.5	1	19	81	----
625	Walnut Creek near Carroll (103)	03229750	38.5	9	----	76	15
626	Walnut Creek near Groveport (117)	03229770	38.0	13	2	80	5
627	Big Darby Creek near West Jefferson (180)	03230230	37.0	----	2	85	14
628	Little Darby Creek near Irwin (180)	03230250	37.8	----	1	99	----
629	Little Darby Creek at West Jefferson (180)	03230310	38.2	----	1	99	----
630	Sugar Creek near Rock Mills (186)	03231800	39.8	14	----	86	----
631	Clear Creek near Hillsboro (186)	03232480	43.2	12	87	1	----
632	Salt Creek at Adelphi (117)	03235090	39.2	4	14	70	13
641	Paramour Creek near Leesville (316)	04195950	36.5	----	----	100	----
642	Sandusky River near North Robinson (316)	04195970	36.5	----	----	100	----

Table 10. Glacial-geology and sediment-thickness characteristics for low-flow partial-record (LFPR) stations in Ohio

Basin identifier (fig. 19)	Station name (index station basin identifier)	Percentage of basin containing					Percentage of basin thickness			
		Coarse-grained sediments	Fine-grained sediments	Till	Patchy Quaternary	Other	0–50 feet	51–100 feet	101–200 feet	201–400 feet
605	Hugle Run at Malvern (48)	18	----	57	18	7	79	13	8	----
606	Little Sandy Creek near Robertsville (48)	14	----	42	38	6	78	12	10	----
608	Apple Creek at Wooster (83)	1	----	99	----	----	65	26	9	----
609	Salt Creek at Holmesville (83)	7	----	93	----	----	84	14	1	----
611	Hocking River at Union Street at Lancaster (117)	18	5	77	----	----	73	9	17	2
612	Center Branch Rush Creek near Junction City (117)	----	12	----	20	68	98	2	----	----
613	Rush Creek near Junction City (117)	----	10	----	46	44	98	2	----	----
614	Clear Creek at Clearport (116)	3	17	76	4	----	98	2	----	----
615	West Branch Shade River at Chester (125)	----	----	----	----	100	100	----	----	----
616	Middle Branch Shade River at Chester (125)	----	----	----	----	100	100	----	----	----
617	Campaign Creek near Gallipolis (142)	----	----	----	----	100	100	----	----	----
618	Ice Creek at Ironton (142)	----	----	----	----	100	100	----	----	----
619	Fulton Creek near Radnor (151)	----	----	100	----	----	100	----	----	----
620	Bokes Creek near Warrensburg (151)	----	----	100	----	----	62	39	----	----
621	Mill Creek near Broadway (151)	1	11	88	----	----	31	63	6	1
622	Mud Run near Caledonia (155)	----	----	100	----	----	14	86	----	----
623	Flat Run near Caledonia (155)	----	----	100	----	----	59	41	----	----
624	Blacklick Creek near Brice (103)	2	----	98	----	----	44	26	21	9
625	Walnut Creek near Carroll (103)	----	25	75	----	----	32	8	26	33
626	Walnut Creek near Groveport (117)	3	10	87	----	----	27	9	35	29
627	Big Darby Creek near West Jefferson (180)	5	1	94	----	----	23	46	32	----
628	Little Darby Creek near Irwin (180)	12	----	88	----	----	2	7	91	----
629	Little Darby Creek at West Jefferson (180)	3	----	97	----	----	12	24	65	----
630	Sugar Creek near Rock Mills (186)	----	----	100	----	----	15	73	12	----
631	Cleaar Creek near Hillsboro (186)	19	42	40	----	----	99	1	----	----
632	Salt Creek at Adelphi (117)	7	16	73	4	1	79	5	16	----
641	Paramour Creek near Leesville (316)	----	47	53	----	----	78	20	3	----
642	Sandusky River near North Robinson (316)	----	33	67	----	----	73	27	----	----

Appendix A. Results of the quality-control analysis of the median index value from RECESS

The selection of recession segments in RECESS relies on interactive and subjective decisions; thus, it is preferred that only one person run the program (Rutledge, 1998). To ensure consistency among the three analysts involved in this study, data from 29 stations were reanalyzed by one of the other analysts. Although some large between-analyst differences were found for the median recession indices from RECESS, the differences between results with RORA ranged only from 0 to 4.6 percent. (See table below.) Previous studies have shown that the results of RORA are not very sensitive to changes in the recession index (Rutledge, 1998).

[n, number of recession segments chosen; in/yr, inches per year; < , less than]

Basin identifier	Years of record	Initial median recession index (n)	Reviewed median recession index (n)	Initial ground-water recharge (in/yr)	Reviewed ground-water recharge (in/yr)	Percent difference in recharge results
11	1965-93	57.0 (25)	40.5 (16)	9.179	9.557	4
27	1946-62	44.0 (13)	43.2 (13)	8.116	8.125	<1
29	1916-97	63.0 (22)	78.2 (50)	9.024	8.796	2.5
33	1941-98	63.8 (48)	55.6 (20)	11.556	11.714	1.4
48	1939-98	55.9 (46)	79.3 (22)	10.217	9.742	4.6
68	1945-78	44.4 (18)	50.4 (7)	5.993	5.915	1.3
83	1931-98	65.7 (18)	75.7 (41)	9.349	9.175	1.9
116	1940-97	53.7 (15)	75.1 (32)	9.367	9.072	3.1
125	1965-98	38.6 (42)	48.2 (9)	7.51[a] 6.864[b]	7.254[1] 6.781[2]	3.4 1.2
134	1970-83	42.3(11)	40.2 (9)	8.314	8.462	1.8
145	1938-72	41.2 (31)	45.8 (15)	5.373	5.214	3
149	1983-96	56.6 (9)	56.3 (11)	4.807	4.807	0
158	1954-74	49.4 (13)	48.5 (15)	6.091	6.098	<1
172	1938-53	43.6 (15)	44.2 (13)	4.835	4.831	<1
182	1966-81	66.4 (12)	53.4 (6)	8.885	9.235	3.9
186	1927-97	47.7 (10)	51.8 (20)	6.850[c] 6.083[d] 8.828[e]	6.730[3] 5.989[4] 8.650[5]	1.8 1.5 2
193	1946-61	41.3 (13)	42.0 (6)	5.295	5.216	1.5
200	1964-97	49.2 (9)	49.2 (21)	8.797	8.797	0
207	1954-68	52.3 (9)	49.0 (11)	9.254	9.391	1.5
212	1968-83	41.0 (22)	40.9 (15)	8.356	8.356	0
222	1961-73	39.4 (9)	49.1 (10)	4.189	4.005	4.4
238	1958-90	50.3 (11)	79.1 (30)	9.817	9.482	3.4
249	1931-98	65.9 (48)	58.3 (12)	7.799	7.909	1.4
255	1939-99	161.4 (46)	110.0 (44)	11.079	11.280	1.8
271	1939-50	74.4 (10)	55.6 (10)	4.612	4.752	3
271	1986-95	53.9 (13)	56.3 (12)	6.756	6.716	0.6
289	1940-81	71.5 (24)	73.2 (29)	8.024	8.012	<1
358	1963-97	45.4 (12)	73.5 (20)	12.856	12.802	<1
368	1942-66	30.8 (25)	35.2 (9)	5.826	5.577	4.3
372	1924-35	68.4 (15)	68.7 (15)[f]	5.113	5.112	<1
372	1939-47	57.1 (9)	68.7 (15)[f]	5.716	5.590	2.2
372	1950-79	76.1 (30)	68.7 (15)[f]	7.163	7.242	1.1

[a] For the years 1966-83.
[b] For the years 1985-97.
[c] For the years 1927-34.
[d] For the years 1940-55.
[e] For the years 1967-80.
[f] For the years 1925-79.

Appendix B. Ground-water recharge estimates based on mean base-flow index (MBI) only, for additional short-term continuous-record (STCR) stations

Station name	Station number	Drainage area (square miles)	Year of record used	MBI	Ground-water recharge (inches per year) MBI based	
					Range[1]	Value[2]
Beech Creek near Lexington	3087500	30.5	1942	18.7	4	2
Mahoning River near Deerfield	3088500	175	1924-30	32.9	5-7	5
Willow Creek near Deerfield	3089000	11.6	1942	20.6	5-6	3
Mosquito Creek near Cortland	3095500	97.5	1927-28	26.7	5-6	4
Meander Creek at Ohlstown	3096500	78.4	1927-28	26.1	5-6	4
Little Muskingum River at Fay	3115500	258	1926-34	41.0	5-7	7
Huff Run at Mineral City	3121850	12.3	1998-99	69.5	9-12	13
Killbuck Creek at Layland	3139500	503	1924-29	57.5	9-10	10
Will Creek at Birds Run	3142500	730	1929-1935	40.3	5-7	7
Sand Fork near Wakatomika	3144400	1.3	1979-81	63.8	9-10	11
Opossum Run Tributary near Wakatomika	3144450	1.3	1979-81	56.3	9-10	10
West Branch Shade River near Burlington	3159534	22.2	1984	50.4	7-9	9
East Branch Shade River near Tuppers Plains	3159555	37.5	1984	50.9	9-10	9
Strongs Run near Ewington	3201947	15.8	1988-90	30.8	5-6	5
Olentangy River near New Winchester	3222500	49.4	1947-48	29.1	5-6	4
Linworth Road Creek at Columbus	3226870	2	1979-80	43.8	7-9	7
Little Darby Creek at West Jefferson	3230310	162	1993-99	50.8	9-10	9
Hellbranch Run near Harrisburg	3230450	37	1993-99	41.2	5-7	7
Todd Fork near Wilmington	3243000	22.2	1943	46.5	7-9	8
Cowan Creek near Wilmington	3243500	32	1943-46	33.7	5-7	5
West Fork Mill Creek at Mount Healthy	3256000	7.9	1950-52	16.7	4	2
Mad River at West Liberty	3266560	36.6	1994-99	81.2	9-12	15
Chapman Creek at Tremont City	3267600	24	1968	51.5	9-10	9
St. Joseph River near Blakeslee	4177500	394	1927-31	58.6	9-10	10
Swan Creek at Toledo	4194000	199	1946-47	52.5	9-10	9
Tymochtee Creek at Crawford	4196800	229	1965-71	29.9	5-6	4
Old Woman's Creek at Berlin Road	4199155	22.1	1988-99	32.4	5-6	5
Vermilion River near Fitchville	4199287	112	1991-92	35.8	5-7	6
Yellow Creek at Ghent	4206208	12.7	1992-97	67.7	9-12	12
North Fork at Bath	4206210	2.8	1992-97	41.4	5-7	7
North Fork at Bath Center	4206212	5.6	1992-99	44.8	7-9	8
Bath Creek at Bath Center	4206215	3.5	1992-97	46.8	7-9	8
Yellow Creek at Botzum	4206220	30.7	1992-99	54.1	9-10	9

[1] Range is based on the 25-75 percent interquartile range in figure 16.

[2] Value was calculated from the regression equation shown in figure 9a.