A Generalized Estimate of Ground-Water-Recharge Rates in the Lower Peninsula of Michigan

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Michigan Basin Regional Aquifer-System Analysis

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By David J. Holtschlag

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square inch (in^2)	6.542	square centimeter
square mile (mi^2)	2.590	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by the following formula:

$$°C = (°F - 32)/1.8$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

A generalized estimate of natural ground-water-recharge rates was developed by analysis of streamflow, precipitation, and basin-characteristics data. Streamflow data were analyzed to determine the ground-water-discharge component of gaged areas. Long-term precipitation data were used to adjust ground-water-discharge data to reflect long-term average recharge characteristics. Basin-characteristics data were used to aid in the interpolation of recharge characteristics within gaged and ungaged areas. The generalized estimate provides a consistent method for approximating recharge rates in the Lower Peninsula of Michigan.

Ground-water-discharge and surface-water-runoff components were determined by use of a hydrograph-separation-analysis technique known as streamflow partitioning. Data were analyzed from 114 selected basins having a total of 3,456 station-years of daily streamflow record. Annual ground-water discharge ranged from 0.19 to 22.7 inches per year. The average ground-water discharge was 8.41 inches per year. The average annual percentage of streamflow identified as ground-water discharge ranged from 29.6 to 97.0 percent.

Basinwide average ground-water discharges were adjusted to provide consistent estimates of recharge from streamflow data collected during different intervals of time. A set of 114 dynamic regression equations relate annual precipitation to annual ground-water discharge in each basin. The equations explained from 18.6 to 75.8 percent of the variation in annual ground-water discharges among the selected basins. Normal basin recharge rates were computed by use of these equations and the normal precipitation for 1951–80 for each selected basin.

A multiple-regression equation was developed to estimate the spatial variation of natural recharge within the Lower Peninsula of Michigan. Selected explanatory variables include (1) latitude and longitude of the basin centroid, (2) surficial geologic material classifications of outwash sand and coarse-textured till, and (3) land-use classifications of deciduous forests and coniferous forests. The equation accounts for 71 percent of the variability of normal basin recharge rates.

Coefficients of the regression equation, which were computed by use of a generalized least-squares procedure, indicate that recharge generally increases from north to south and from east to west throughout the Lower Peninsula. This geographic variation is thought to be associated with climatic factors. The regression coefficients associated with surficial geologic materials classified as outwash sand or coarse-textured till and with the forest land-use classifications were positive. The positive coefficients are thought to be associated with infiltration capacities of soils associated with the selected surficial materials and land-use classifications. Maps showing the generalized estimate of recharge and the relative uncertainty of the generalized estimate were developed.

INTRODUCTION

The Michigan Basin Regional Aquifer-System Analysis (RASA) study area encompasses about 29,000 square miles (mi^2) in the center of the Lower Peninsula of Michigan. The objective of the Michigan Basin RASA is to aid in the effective management of the region's ground-water resources by providing information on the hydrogeology and the geochemistry of aquifers in near-surface bedrock and glacial deposits (Mandle, 1986, p. 15). Information on components was obtained by (1) estimating the water budget, (2) describing the geologic framework and the hydraulic characteristics of the aquifer materials, (3) modeling ground-water levels and flow nets, and (4) assessing the water-quality characteristics and the geochemistry of the regional aquifer system.

The study of regional ground-water recharge described herein helps to meet the objective of the Michigan Basin RASA by providing an estimate of the spatial variation of natural ground-water-recharge rates to the surficial geologic materials within the Lower Peninsula. Natural recharge refers to recharge that results directly from infiltration of precipitation or from runoff and subsequent infiltration from surface-water bodies (Allison, 1988, p. 49). Artificial recharge and recharge induced by irrigation are not considered here.

Direct measurement of recharge is difficult. Closed-bottom lysimeters buried beneath the rooting zone (Routson and Johnson, 1990) provide a direct measurement. Unfortunately, such lysimeter data are generally unavailable. Therefore, numerous techniques for estimating recharge have been developed.

Common techniques for estimating point or average recharge rates include (1) chemical-tracer studies, (2) tritium isotopic studies, (3) numerical simulation of mechanistic processes, (4) water-balance studies, (5) studies of ground-water-level fluctuation, (6) derivation of empirical relations based on precipitation data, and (7) studies based on hydrograph separation of streamflow records. Although none of these techniques is entirely reliable (Simmers, 1988, p. xi), hydrograph separation was selected for this study because of its widespread use for recharge estimation, the availability of supporting data, and the need to apply the technique across an area as large and diverse as the Lower Peninsula.

Hydrograph separation is an attempt to identify the surface and subsurface flow components of streamflow. The subsurface component is primarily ground-water discharge that originates as recharge. Many different techniques for hydrograph separation have been devised (Barnes, 1939; Snyder, 1939; Chow, 1964; Pettyjohn and Henning, 1979; Shirmohammadi and others, 1984, 1987; Nathan and McMahon, 1990; Rutledge, 1991, 1993). Because of the large amount of streamflow data available for the Lower Peninsula of Michigan, only those separation techniques that have been adapted for computer processing were considered feasible for this application.

Recharge rates computed by use of hydrograph-separation techniques represent a spatial and temporal average for a specific basin during a specific time interval of data collection. If the technique is applied to more than one basin in a streamflow-data-collection network and if measurement intervals differ among the basins, the resulting set of recharge rates may be inconsistent because of temporal variations in recharge. This unwanted source of variation was eliminated in this study by adjusting the set of recharge rates to represent a common period of data collection. Finally, an interpolation technique was used to describe the spatial variation of recharge rates within gaged and ungaged basins.

The Michigan Basin RASA has built upon the work of other scientists who have described recharge (Simmers, 1988) and the hydrogeology of Michigan (Mandle and Westjohn, 1989; Rheaume, 1990). Previous investigators (McDonald, 1981; Grannemann and Twenter, 1985; Delcore and Larson, 1987; Straw and others, 1989) have provided estimates of local recharge in Michigan; generalized recharge rates have not been previously available.

Purpose and Scope

The purpose of this report is to describe (1) a set of streamflow-gaging stations for use in recharge estimation, (2) a hydrograph-separation technique appropriate for the selected set of stations, (3) a set of recharge estimates from the hydrograph-separation analysis that represent a common base period, (4) the recharge estimates within and between gaged basins in the Lower Peninsula, and (5) the spatial variations and relative uncertainties in the ground-water-recharge rates.

A definitive analysis of alternative recharge-estimation techniques is outside the scope of this report. The relation between estimated recharge and true recharge is generally unknown because insufficient direct measurements of recharge are available. However, separation techniques are commonly used for recharge estimation, and different separation techniques may produce similar estimates of recharge. Unfortunately, any uncertainty associated with the difference between estimated and true recharge rates could not be assessed in this analysis. (For a recent review of hydrograph-separation techniques, see Nathan and McMahon (1990)). Neither does this report describe the seasonal or annual variations of recharge; only a long-term average recharge is given, which corresponds to long-term average precipitation for 1951–80 in Michigan. Timing of recharge, which can have important implications for analysis of transient-flow conditions in aquifers, cannot be assessed by use of the selected information.

The report describes an interpolation method used to develop the generalized estimate of natural recharge. The interpolation method is based on a statistical relation between the main effects of readily measurable basin characteristics and basinwide recharge rates. Interaction and higher order effects and human activities that locally affect recharge could not be determined from the available data. Thus, alternative recharge estimators that reliably account for localized factors would supersede the generalized estimate in this report.

Acknowledgments

Dr. David Lusch, Specialist of the Center for Remote Sensing at Michigan State University, provided the digital data used to delineate basin boundaries, determine basin characteristics, and map the generalized estimate and the relative uncertainty of recharge. Dr. Fred Nurnberger, State Climatologist with the Michigan Department of Agriculture, provided normal precipitation data needed to compute normal basin recharge. Mr. David Hamilton, Chief of the Hydrologic Studies Section, Land and Water Management Division, Michigan Department of Natural Resources, aided the initial selection of streamflow-gaging stations used in the recharge analysis.

METHODS OF STUDY

The spatial variation of ground-water recharge was estimated by analyzing daily streamflow records, precipitation data, and basin-characteristics data. Streamflow data were obtained from records maintained by the U.S. Geological Survey (USGS). Annual precipitation data were obtained from a compilation of precipitation data from the National Climatic Data Center distributed by EarthInfo Incorporated. Normal (30-year (yr) average) precipitation data for the period 1951–80 were provided by Fred Nurnberger (State Climatologist, Michigan Department of Agriculture, written commun., 1992). Basin-characteristics data were obtained from the Center for Remote Sensing at Michigan State University (David Lusch, written commun., 1992).

Estimation of generalized recharge rates was a three-step process. First, daily values of streamflow from selected gaging stations were partitioned into ground-water-discharge and surface-water-runoff components. Second, the annual ground-water-discharge component was related to annual precipitation in a series of basin-specific regression equations. The steady-state solution of these dynamic regression equations (Pankratz, 1991, p. 115) at the normal precipitation rate for the period 1951–80 was used to define the normal recharge for each basin. Third, an equation was developed to relate the variation of normal recharge among basins to readily measurable basin characteristics. The recharge equation was used to map the spatial variation and describe the relative uncertainty associated with the generalized recharge estimate. A detailed account of this process follows.

Selection of Streamflow-Gaging Stations

A set of 114 USGS streamflow-gaging stations was selected for analysis (table 1). The criteria for selection follow: (1) gaging station location in the Lower Peninsula of Michigan; (2) a minimum of 10 yr of continuous streamflow data through water year 1991; (3) a drainage area of the gaged basin less than 1,500 mi^2; (4) no significant effects of regulation, diversion, or augmentation on streamflow; and (5) surface-water and ground-water divides that are thought to be approximately coincident. These criteria were developed to eliminate stations for which hydrograph separation would likely lead to inaccurate estimates of recharge.

All hydrograph-separation techniques are implicitly based on the assumption that variations in streamflow are the eventual response of the basin to precipitation. Some adjustment is generally provided to account for the natural attenuation of streamflow

Table 1. U.S. Geological Survey streamflow-gaging stations selected for hydrograph-separation analysis
[USGS, U.S. Geological Survey; mi², square miles]

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Station name	Drainage area (mi²)	Latitude of station	Longitude of station
A	1	04096400	St. Joseph River near Burlington, Mich.	201	42°06'10"	85°02'25"
A	2	04096515	South Branch Hog Creek near Allen, Mich.	48.7	41°56'55"	84°49'40"
A	3	04096600	Coldwater Creek near Hodunk, Mich.	293	42°01'45"	85°06'25"
A	4	04096900	Nottawa Creek near Athens, Mich.	162	42°03'20"	85°18'30"
A	5	04097170	Portage River near Vicksburg, Mich.	68.2	42°06'53"	85°29'08"
A	6	04097540	Prairie River near Nottawa, Mich.	106	41°53'18"	85°24'34"
A	7	04098500	Fawn River near White Pigeon, Mich.	192	41°46'56"	85°35'00"
A	8	04101800	Dowagiac River at Sumnerville, Mich.	255	41°54'48"	86°12'47"
A	9	04102500	Paw Paw River at Riverside, Mich.	390	42°11'10"	86°22'06"
A	10	04102700	South Branch Black River near Bangor, Mich.	83.6	42°21'15"	86°11'15"
A	11	04105000	Battle Creek at Battle Creek, Mich.	241	42°19'55"	85°09'15"
A	12	04105500	Kalamazoo River near Battle Creek, Mich.	824	42°19'26"	85°11'51"
A	13	04105700	Augusta Creek near Augusta, Mich.	38.9	42°21'12"	85°21'14"
A	14	04106000	Kalamazoo River at Comstock, Mich.	1,010	42°17'08"	85°30'50"
A	15	04108600	Rabbit River near Hopkins, Mich.	71.4	42°38'32"	85°43'19"
A	16	04108800	Macatawa River near Zeeland, Mich.	65.8	42°46'40"	86°01'00"
A	17	04109000	Grand River at Jackson, Mich.	174	42°17'05"	84°24'30"
A	18	04110000	Orchard Creek at Munith, Mich.	49	42°23'35"	84°15'50"
A	19	04111500	Deer Creek near Dansville, Mich.	16.3	42°36'30"	84°19'15"
A	20	04112000	Sloan Creek near Williamston, Mich.	9.3	42°40'33"	84°21'50"
A	21	04112500	Red Cedar River at East Lansing, Mich.	355	42°43'40"	84°28'40"
A	22	04114500	Looking Glass River near Eagle, Mich.	281	42°49'45"	84°46'40"
A	23	04115000	Maple River at Maple Rapids, Mich.	434	43°06'35"	84°41'35"
A	24	04116500	Flat River near Smyrna, Mich.	528	43°03'10"	85°15'50"
A	25	04117000	Quaker Brook near Nashville, Mich.	7.6	42°33'57"	85°05'37"
A	26	04117500	Thornapple River near Hasting, Mich.	385	42°36'57"	85°14'11"
A	27	04118000	Thornapple River near Caledonia, Mich.	773	42°48'40"	85°29'00"
A	28	04118500	Rogue River near Rockford, Mich.	234	43°04'56"	85°35'27"
B	29	04121000	Muskegon River near Merritt, Mich.	355	44°20'08"	84°53'24"
B	30	04121300	Clam River at Vogel Center, Mich.	243	44°12'02"	85°03'10"
B	31	04121500	Muskegon River at Evart, Mich.	1,450	43°53'57"	85°15'19"
B	32	04121900	Little Muskegon River near Morley, Mich.	138	43°30'09"	85°20'33"
B	33	04122100	Bear Creek near Muskegon, Mich.	14.8	43°17'19"	86°13'22"
B	34	04122200	White River near Whitehall, Mich.	406	43°27'51"	86°13'57"
B	35	04122500	Pere Marquette River at Scottville, Mich.	681	43°56'42"	86°16'43"
B	36	04123000	Big Sable River near Freesoil, Mich.	127	44°07'13"	86°16'48"
B	37	04123500	Manistee River near Grayling, Mich.	159	44°41'35"	84°50'50"
B	38	04124000	Manistee River near Sherman, Mich.	857	44°26'11"	85°41'55"
B	39	04124500	East Branch Pine River near Tustin, Mich.	63	44°06'10"	85°31'00"
B	40	04125000	Pine River near Le Roy, Mich.	118	44°03'50"	85°32'55"
B	41	04125500	Pine River near Hoxeyville, Mich.	251	44°12'11"	85°47'58"
B	42	04126200	Little Manistee River near Freesoil, Mich.	200	44°11'00"	86°10'00"
B	43	04128000	Sturgeon River near Wolverine, Mich.	198	45°17'56"	84°36'40"
B	44	04129000	Pigeon River near Vanderbilt, Mich.	62.6	45°10'15"	84°26'18"

Table 1. U.S. Geological Survey streamflow-gaging stations selected for hydrograph-separation analysis—Continued

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Station name	Drainage area (mi²)	Latitude of station	Longitude of station
B	45	04129500	Pigeon River at Afton, Mich.	159	45°22'26"	84°30'54"
B	46	04131500	Rainy River near Ocqueoc, Mich.	87.9	45°24'30"	84°10'45"
B	47	04132500	Thunder Bay River near Hillman, Mich.	232	45°00'30"	83°58'21"
B	48	04134000	North Branch Thunder Bay River near Bolton, Mich.	184	45°08'30"	83°36'21"
B	49	04135500	Au Sable River at Grayling, Mich.	110	44°39'35"	84°42'45"
B	50	04135600	East Branch Au Sable River at Grayling, Mich.	76.0	44°40'08"	84°42'20"
B	51	04135700	South Branch Au Sable River near Luzerne, Mich.	401	44°36'53"	84°27'20"
C	52	04138000	East Branch Au Gres River at McIvor, Mich.	84.0	44°13'57"	83°42'03"
C	53	04138500	Au Gres River near National City, Mich.	169	44°10'26"	83°44'36"
C	54	04139000	Houghton Creek near Lupton, Mich.	29.7	44°23'45"	84°02'50"
C	55	04139500	Rifle River at "The Ranch" near Lupton, Mich.	56.8	44°23'06"	84°02'18"
C	56	04140000	Prior Creek near Selkirk, Mich.	21.4	44°20'06"	84°04'06"
C	57	04140500	Rifle River at Selkirk, Mich.	117	44°18'48"	84°04'10"
C	58	04141000	South Branch Shepards Creek near Selkirk, Mich.	1.15	44°18'28"	84°05'13"
C	59	04141500	West Branch Rifle River near Selkirk, Mich.	52.0	44°15'40"	84°06'30"
C	60	04142000	Rifle River near Sterling, Mich.	320	44°04'21"	84°01'12"
C	61	04143500	North Branch Kawkawlin River near Kawkawlin, Mich.	101	43°40'05"	83°58'13"
C	62	04144000	Shiawassee River at Byron, Mich.	368	42°49'25"	83°56'45"
C	63	04145000	Shiawassee River near Fergus, Mich.	637	43°15'17"	84°06'20"
C	64	04146000	Farmers Creek near Lapeer, Mich.	55.3	43°02'41"	83°20'14"
C	65	04146063	South Branch Flint River near Columbiaville, Mich.	221	43°09'34"	83°21'03"
C	66	04147990	Butternut Creek near Genesee, Mich.	34.7	43°08'09"	83°35'57"
C	67	04148200	Swartz Creek near Holly, Mich.	12.1	42°49'39"	83°37'42"
C	68	04148300	Swartz Creek at Flint, Mich.	115	42°59'16"	83°43'57"
C	69	04148440	Thread Creek near Flint, Mich.	54.4	42°58'30"	83°38'09"
C	70	04148720	Brent Run near Montrose, Mich.	20.8	43°10'12"	83°50'03"
C	71	04150000	S. Branch Cass River near Cass City, Mich.	238	43°34'01"	83°06'43"
C	72	04150500	Cass River at Cass City, Mich.	359	43°35'03"	83°10'34"
C	73	04151500	Cass River at Frankenmuth, Mich.	841	43°19'40"	83°44'53"
C	74	04152500	Tobacco River at Beaverton, Mich.	487	43°52'43"	84°28'18"
C	75	04153500	Salt River near North Bradley, Mich.	138	43°42'10"	84°28'14"
C	76	04154000	Chippewa River near Mount Pleasant, Mich.	416	43°37'32"	84°42'28"
C	77	04154500	Chippewa River near Midland, Mich.	597	43°35'40"	84°22'10"
C	78	04157500	State Drain near Sebewaing, Mich.	67.3	43°43'00"	83°26'00"
C	79	04158000	Columbia Drain near Sebewaing, Mich.	33.9	43°43'38"	83°23'46"
C	80	04158500	Pigeon River near Owendale, Mich.	53.2	43°45'49"	83°14'46"
D	81	04159500	Black River near Fargo, Mich.	480	43°05'32"	82°37'05"
D	82	04159900	Mill Creek near Avoca, Mich.	169	43°03'16"	82°44'05"
D	83	04160000	Mill Creek near Abbottsford, Mich.	208	43°02'42"	82°36'50"
D	84	04160570	North Branch Belle River at Imlay City, Mich.	18	43°01'49"	83°04'02"
D	85	04160600	Belle River at Memphis, Mich.	151	42°54'03"	82°46'09"
D	86	04160800	Sashabaw Creek near Drayton Plains, Mich.	20.9	42°43'12"	83°21'13"
D	87	04160900	Clinton River near Drayton Plains, Mich.	79.2	42°39'37"	83°23'25"
D	88	04161100	Galloway Creek near Auburn Heights, Mich.	17.9	42°40'02"	83°12'02"
D	89	04161500	Paint Creek near Lake Orion, Mich.	38.5	42°46'03"	83°13'12"

Table 1. U.S. Geological Survey streamflow-gaging stations selected for hydrograph-separation analysis—Continued

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Station name	Drainage area (mi²)	Latitude of station	Longitude of station
D	90	04161540	Paint Creek at Rochester, Mich.	70.9	42°41'18"	83°08'35"
D	91	04161580	Stony Creek near Romeo, Mich.	25.6	42°48'03"	83°05'25"
D	92	04161800	Stony Creek near Washington, Mich.	68.2	42°42'55"	83°05'31"
D	93	04163400	Plum Brook at Utica, Mich.	16.5	42°36'05"	83°04'27"
D	94	04163500	Plum Brook near Utica, Mich.	22.9	42°35'01"	83°01'49"
D	95	04164100	East Pond Creek at Romeo, Mich.	21.8	42°49'21"	83°01'13"
D	96	04164300	East Branch Coon Creek at Armada, Mich.	13	42°50'45"	82°53'06"
D	97	04164500	North Branch Clinton River near Mount Clemens, Mich.	199	42°37'45"	82°53'25"
D	98	04164800	Middle Branch Clinton River at Macomb, Mich.	41.0	42°42'23"	82°57'33"
D	99	04166000	River Rouge at Birmingham, Mich.	33.3	42°32'45"	83°13'25"
D	100	04166100	River Rouge at Southfield, Mich.	87.9	42°26'52"	83°17'52"
D	101	04166200	Evans Ditch at Southfield, Mich.	9.5	42°27'28"	83°16'03"
D	102	04166300	Upper River Rouge at Farmington, Mich.	17.5	42°27'52"	83°22'11"
D	103	04167000	Middle River Rouge near Garden City, Mich.	99.9	42°20'55"	83°18'45"
D	104	04168000	Lower River Rouge at Inkster, Mich.	83.2	42°18'00"	83°18'00"
D	105	04169500	Huron River at Commerce, Mich.	57.3	42°35'25"	83°29'05"
D	106	04170000	Huron River at Milford, Mich.	132	42°34'44"	83°37'36"
D	107	04171500	Ore Creek near Brighton, Mich.	31.0	42°29'40"	83°48'05"
D	108	04172000	Huron River near Hamburg, Mich.	308	42°27'55"	83°48'00"
D	109	04173000	Huron River near Dexter, Mich.	522	42°23'10"	83°54'40"
D	110	04173500	Mill Creek near Dexter, Mich.	128	42°18'00"	83°53'55"
D	111	04175340	Stony Creek at Oakville, Mich.	68.0	42°05'05"	83°34'43"
D	112	04175600	River Raisin near Manchester, Mich.	132	42°10'05"	84°04'34"
D	113	04175700	River Raisin near Tecumseh, Mich.	267	41°56'35"	83°56'45"
D	114	04176000	River Rasin near Adrian, Mich.	463	41°54'15"	83°58'50"

peaks that commonly occurs with distance along the stream channel. These adjustments, however, cannot account for sudden attenuations associated with storage in lakes and reservoirs or effects associated with flow regulation, augmentation, or diversion. Therefore, gaging stations where channel storage, regulation, diversion, or flow augmentation was thought to significantly affect peak-streamflow attenuation rates were not included in the analysis.

The identification of gaged basins and of the variability of annual ground-water discharge was facilitated by dividing the Lower Peninsula into four zones (fig. 1). Each zone contains between 23 and 34 gaging stations and corresponds to one or two subregional hydrologic units, as delineated on the hydrologic unit map for Michigan (U.S. Geological Survey, 1974). Approximate basin boundaries within each zone are shown in figures 2 through 5.

Identifying the Ground-Water Component of Streamflow

The purpose of hydrograph separation is to subdivide daily values of streamflow into ground-water and surface-runoff components. The long-term average ground-water component provides an estimate of the long-term average observable recharge rate. Observable recharge is defined as that part of total recharge that emerges as streamflow within the basin. Recharge that flows out of the basin as ground water or that is lost to riparian evapotranspiration is considered unobservable. In this report, the term "recharge" refers to observable recharge.

Numerous techniques have been developed for hydrograph separation. Because of the importance and inherent difficulties of establishing the most appropriate technique under a wide variety of hydraulic and geologic conditions, refinements of hydrograph-separation techniques continue to stimulate research activity (Nathan and McMahon, 1990). White and Sloto (1990) and Rutledge (1993) have developed or implemented automated techniques. Automated techniques were needed in this study because of the large amount of data analyzed and because of the need for consistency, reproducibility, and speed of data processing.

In this study, the hydrograph-separation technique referred to as "streamflow partitioning" (Rutledge, 1993) was used because the technique (1) was developed specifically to estimate recharge in the humid, eastern part of the United States, (2) produces estimates that are in close agreement with estimates derived from other manual and automated techniques of streamflow separation, (3) has data requirements that are consistent with available data, and (4) can be used efficiently with existing computational resources.

Streamflow partitioning consists of two steps: (1) ground-water discharge is set equal to streamflow during times of negligible surface runoff, and (2) ground-water discharge between these periods (during apparent surface-runoff events) is interpolated. Periods of surface runoff are inferred from an iterative analysis of the hydrograph-recession characteristics. The streamflow partition in figure 6 shows the volume of flow below the partition as the ground-water component and the volume of flow above the partition as the surface-runoff component.

Estimating Normal Basin Recharge Rates

Annual ground-water discharges varied among stations. Some of this variation is expected because of variation in annual precipitation that is the source of ground-water discharge. Additional variation is expected because of annual changes in ground-water storage in the aquifer. Although the average ground-water discharge over the period of record provides an estimate of the long-term average recharge rate, this estimate may not be consistent among stations operated during different time intervals. Any inconsistency would decrease the accuracy of an equation used to estimate the spatial variation of recharge rates.

To ensure a consistent recharge estimate among selected basins, the current year's ground-water discharge was related to basin precipitation and the previous year's ground-water discharge by a set of basin-specific regression equations having the general form

$$q_{i,j} = \beta_{i0} + \beta_{i1} p_{i,j} + \beta_{i2} q_{i,j-1} + \zeta_{i,j} \qquad (1)$$

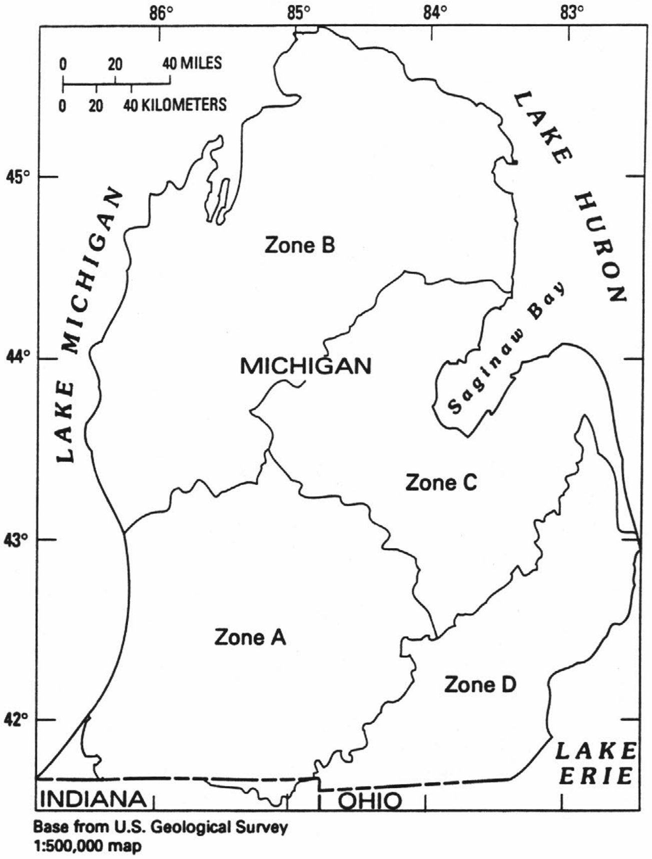


Figure 1. Designated zones in the Lower Peninsula of Michigan.

where

$q_{i,j}$ is the annual ground-water discharge at basin i in year j,

$p_{i,j}$ is the annual mean precipitation at basin i in year j,

$q_{i,j-1}$ is the annual ground-water discharge at basin i in year j–1,

$[\beta_{i0}\ \beta_{i1}\ \beta_{i2}]'$ are a set of ordinary least-squares regression coefficients, which can be written as a column vector $\vec{\beta}_i$ and computed as $(\underline{X}'\underline{X})^{-1}\underline{X}'\vec{q}_i$, where $\underline{X}$ is the matrix of explanatory variables augmented by a column of ones in the first column. The prime symbol indicates a matrix transpose, and the –1 power indicates a matrix inverse. The vector $\vec{q}_i$ contains annual mean discharges from the ith basin, and

$\zeta_{i,j}$ is a random error term that is assumed to be a stationary sequence of independent, normally distributed random variables with mean zero and standard deviation

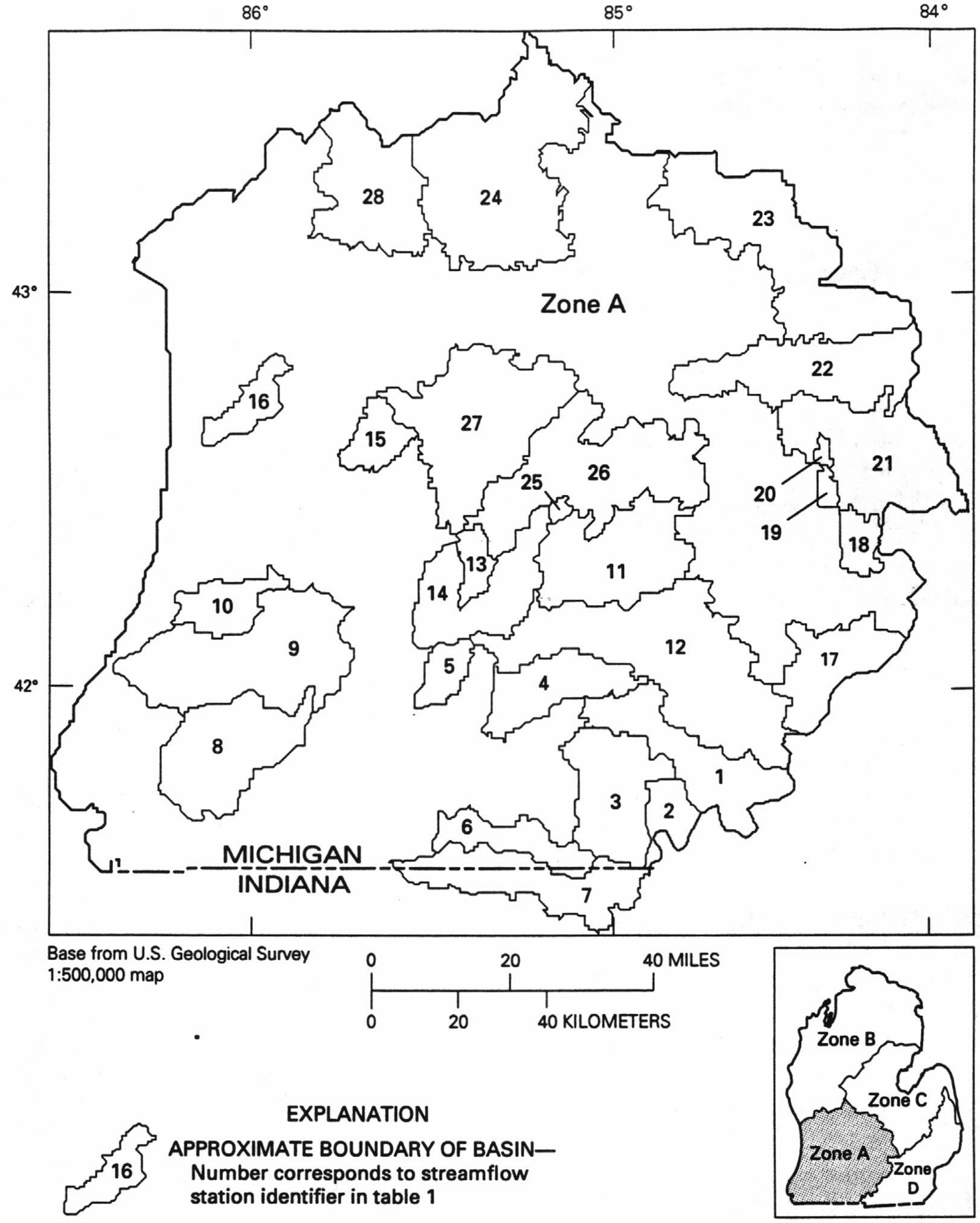


Figure 2. Selected basins in Zone A, Lower Peninsula of Michigan.

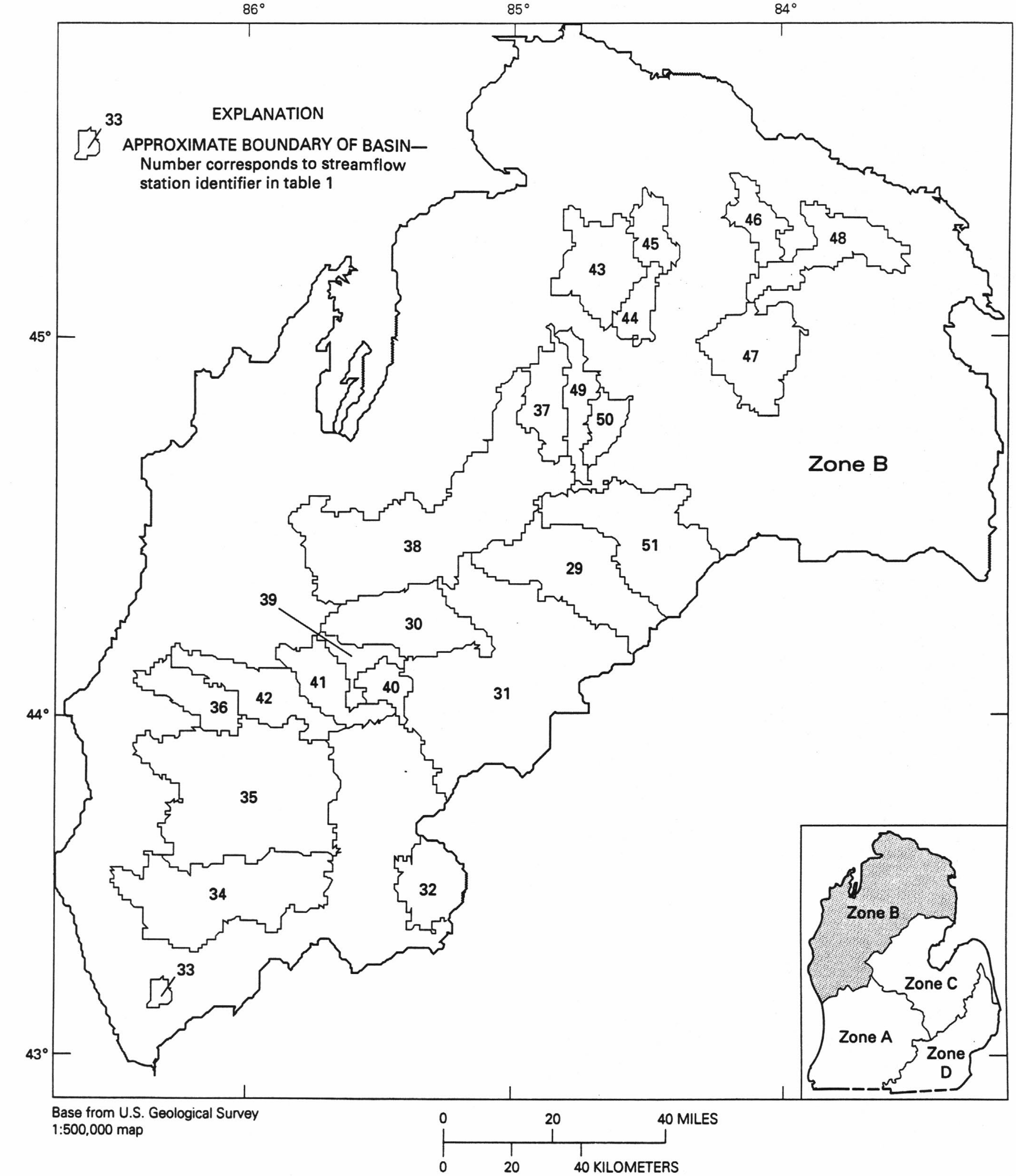


Figure 3. Selected basins in Zone B, Lower Peninsula of Michigan.

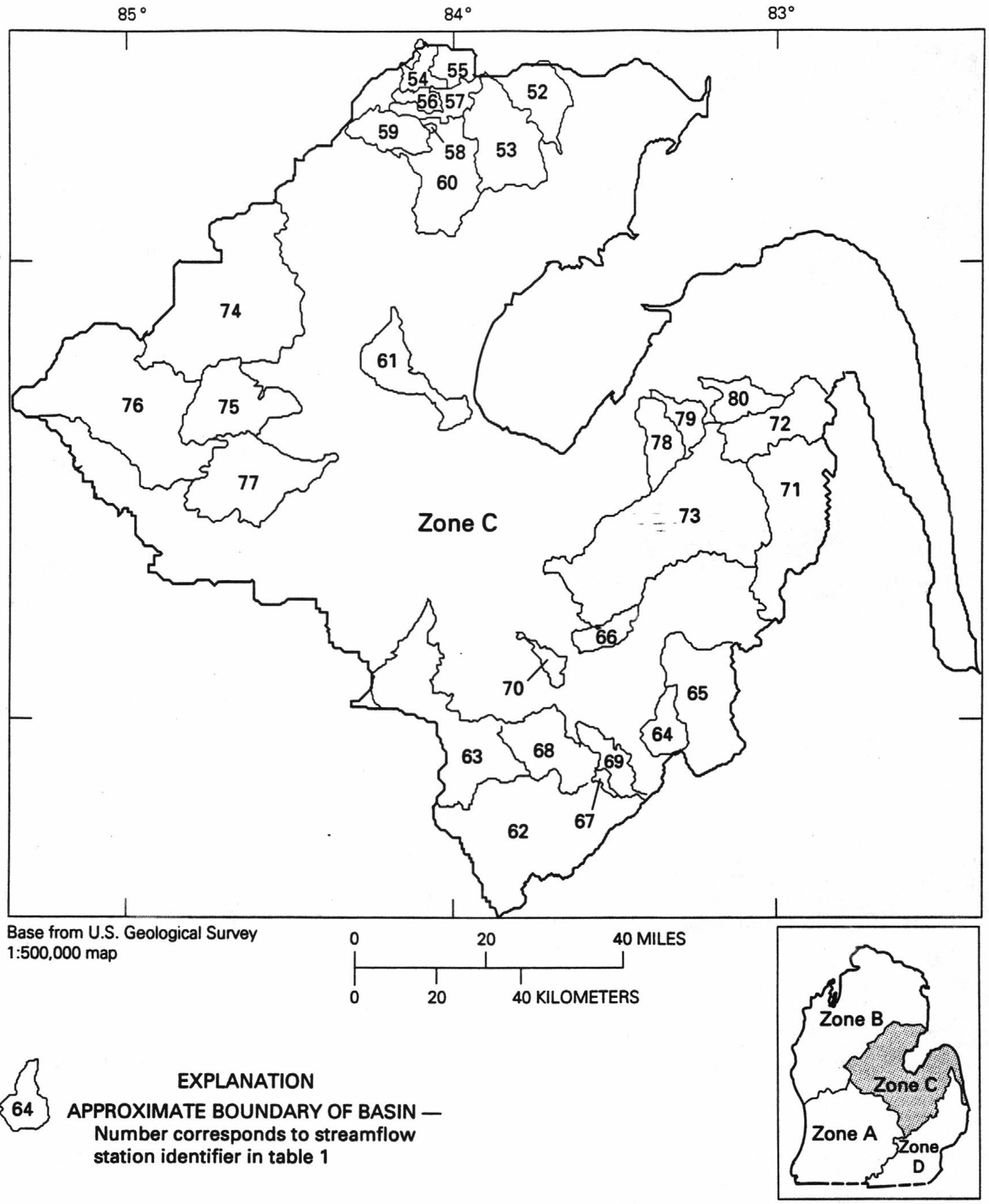


Figure 4. Selected basins in Zone C, Lower Peninsula of Michigan.

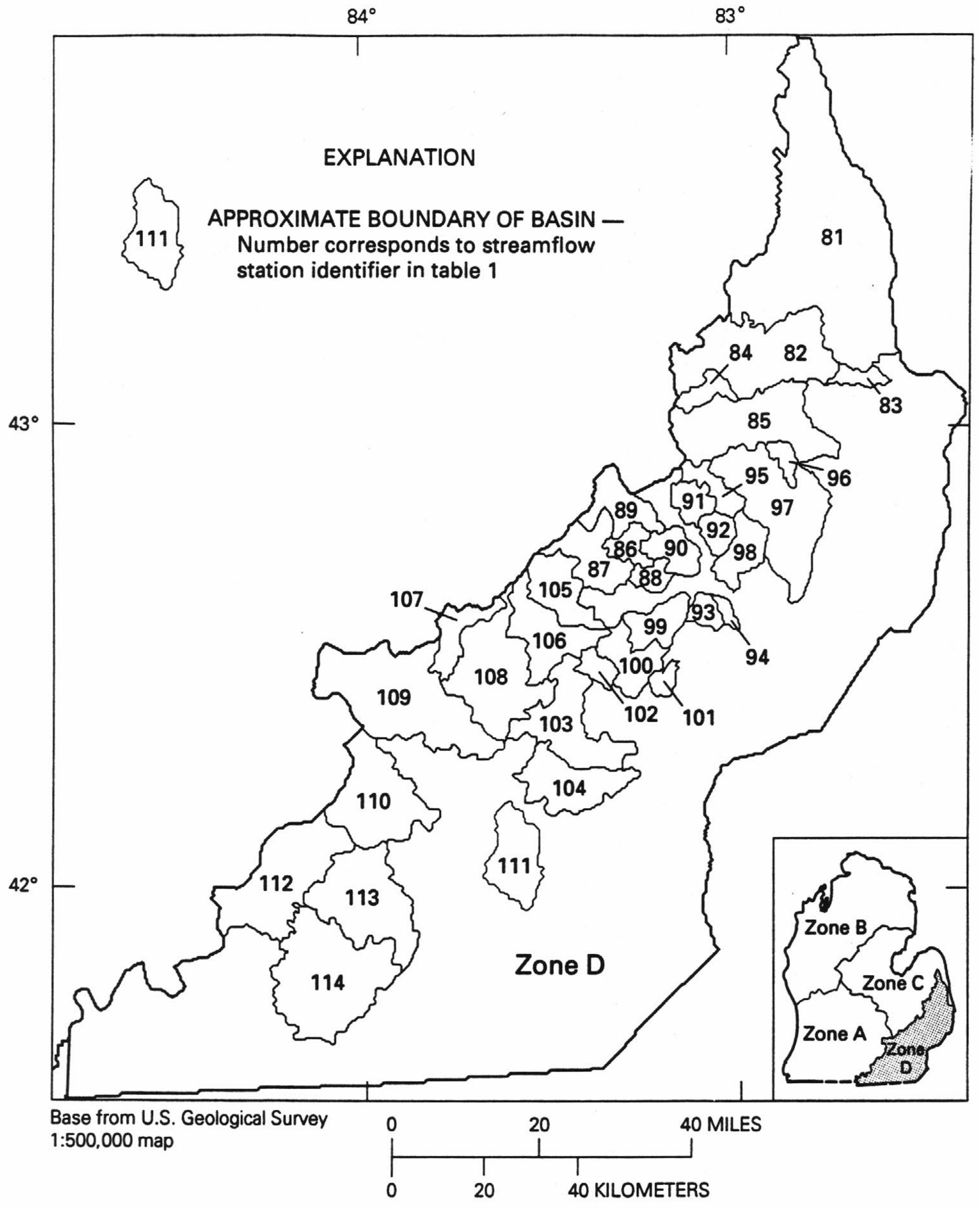


Figure 5. Selected basins in Zone D, Lower Peninsula of Michigan.

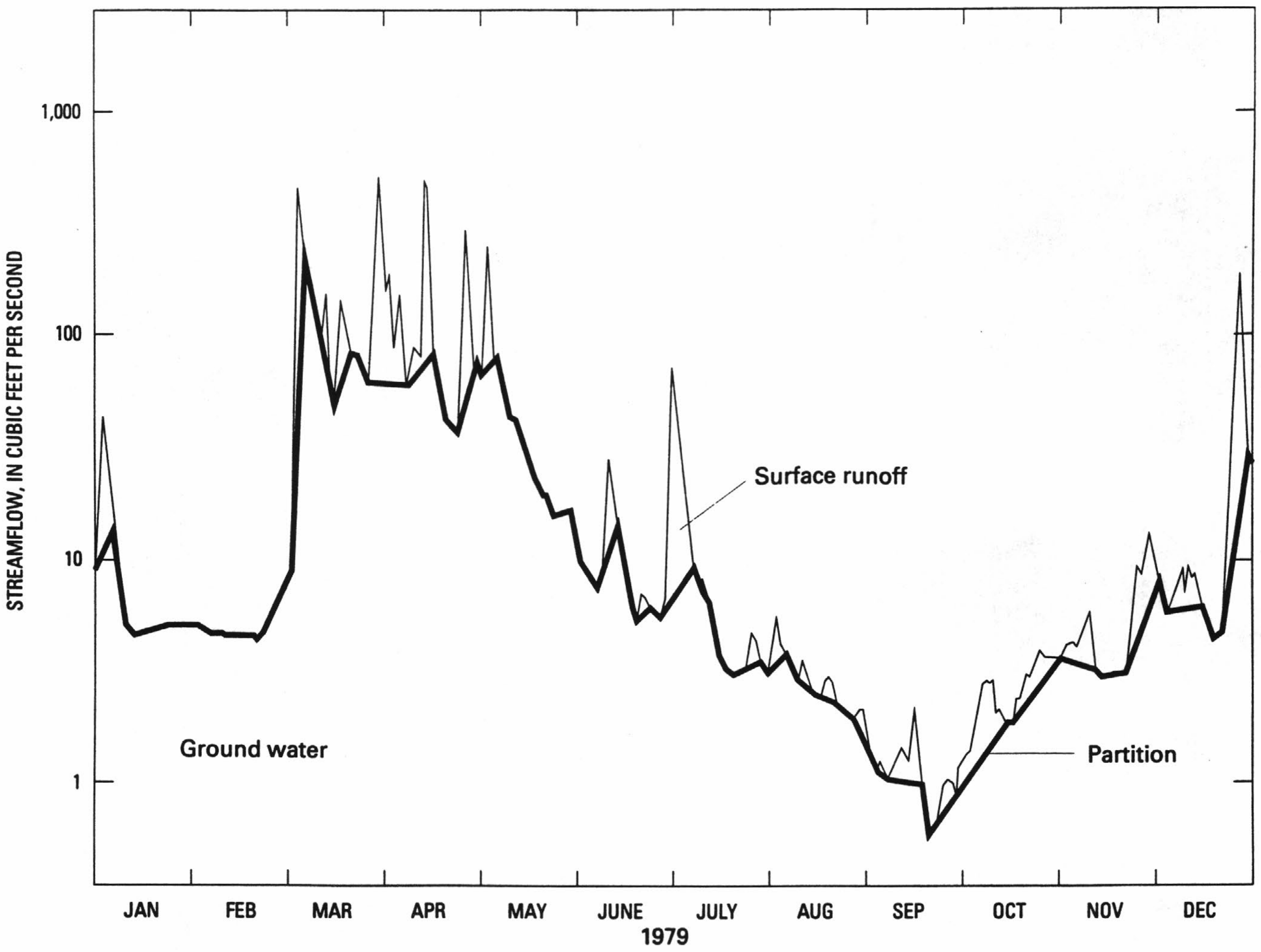


Figure 6. Partition of streamflow in 1979 at Pigeon River near Owendale, Mich.

$$s_i = \sqrt{(n_i - 1 - k)^{-1} \sum_j \zeta_{i,j}^2}\,, \qquad (2)$$

where n_i is the number of years of record at the ith station and

k is the number of parameters.

A consistent set of the normal basin recharge estimates was computed by use of the basin-specific regression equations. The estimate was computed by substituting the normal precipitation for the period 1951–80, p_{iN}, for the annual precipitation. The difference between the mean annual precipitation during the period of record and the normal precipitation provides the basis for the adjustment. To remove the effects of changes in aquifer storage, the normal basin recharge estimate, y_i, was computed as steady-state solution $(q_{i,j} = q_{i,j-1})$ to equation 1 as

$$y_i = \frac{\beta_{i0}}{1 - \beta_{i2}} + \frac{\beta_{i1} p_{iN}}{1 - \beta_{i2}}\,. \qquad (3)$$

The standard error of y_i was computed as

$$S_i = s_i \sqrt{\hat{x}'(\underline{X}'\underline{X})^{-1}\hat{x}}\,, \qquad (4)$$

where $\hat{x}$ is the column vector generally equal to $[1, p_{iN}, y_i]'$.

The true normal basin recharge, Ψ_i, estimated by y_i has a random error component, η_i, such that

$$\Psi_i = y_i - \eta_i\,, \qquad (5)$$

where the expected value of $\eta_i = 0$ and the variance of $\eta_i = S_i^2$ (G.D. Tasker, USGS, written commun., 1992).

Thus, y_i provides a statistically unbiased estimate of Ψ_i with a sampling error that is a function of s_i. However, because some of the ground-water recharge may not appear as streamflow at the gaging station and some recharge may be lost to riparian evapotranspiration, y_i tends to be less than total recharge. The magnitude of the difference between total recharge and observable recharge could not be determined from available data.

Developing a Generalized Estimate of Recharge Rates

Normal basin recharge rates describe spatially averaged recharge rates. Local recharge rates within basins, however, can differ considerably from basin-wide averages because of climatic factors and local variations in basin infiltration capacities. In addition, the basinwide average rates are not directly applicable to ungaged areas. Therefore, a regression equation was developed to interpolate normal basin recharge rates within gaged and ungaged areas by use of selected basin characteristics.

Basin characteristics considered as possible explanatory variables included latitude and longitude of basin centroids (as an index of spatial variations in climate-related factors), mean basin elevation, slope characteristics, surface-permeability characteristics, surficial geological materials, land-use and land-cover characteristics, and surface-drainage characteristics. Locations of basin centroids were determined from maps showing basin boundaries (Croskey and Beall, 1984). Data on the elevation, slope, permeability, surficial geological material, land use and land cover, and surface-drainage characteristics were determined by personnel at the Center for Remote Sensing at Michigan State University (David Lusch, written commun., 1992) from digital maps and related data sets.

The basin-characteristics data and the basin-specific estimates of normal basin recharge were used to develop a recharge equation of the form

$$\vec{y} = \underline{X}\vec{\beta} + \vec{\eta} + \vec{\varepsilon}, \tag{6}$$

where

$\underline{X}$ is an $(n \times p)$ matrix such that n equals the number of observations (gaging stations) and $(p-1)$ is the number of selected basin characteristics augmented by a column of ones,

$\vec{\beta}$ is a $(p \times 1)$ vector of regression coefficients,

$\vec{\eta}$ is an $(n \times 1)$ vector of sampling-error components, and

$\vec{\varepsilon}$ is an $(n \times 1)$ vector of model-error components. The error components are related such that the expected value of $\vec{\varepsilon} + \vec{\eta} = \vec{0}$ and the expected value of $[(\vec{\varepsilon} + \vec{\eta})(\vec{\varepsilon} + \vec{\eta})']$ is designated as the matrix $\underline{\Lambda}$ (G.D. Tasker, USGS, written commun., 1992).

The estimator of the error covariance matrix, $\underline{\Lambda}$, is a symmetric $(n \times n)$ matrix that can be disaggregated into model-error and sampling-error components as

$$\hat{\underline{\Lambda}} = \hat{\gamma}^2 \underline{I}_n + \hat{\underline{\Sigma}}, \tag{7}$$

where

$\hat{\gamma}^2$ is an estimator of the variance of the error inherent in the model,

$\underline{I}_n$ is an $(n \times n)$ identity matrix, and

$\hat{\underline{\Sigma}}$ is an $(n \times n)$ matrix that estimates the sampling-error covariance matrix.

Each element of $\hat{\underline{\Sigma}}$ is computed as

$$\hat{\underline{\Sigma}}_{i,j} = \left\{ \begin{matrix} S_i^2 & \forall\ (i = j) \\ \rho(\zeta_i, \zeta_j) S_i S_j & \forall\ (i \neq j) \end{matrix} \right\}, \tag{8}$$

where

i and j are index rows and columns of the matrix,

$S_i^2 \forall\ (i = j)$ is the sample variance for every $i = j$, and

$\rho(\zeta_i, \zeta_j)$ is the effective spatial correlation function (G.D. Tasker, USGS, written commun., 1992).

The effective spatial correlation function accounts for the spatial correlation and the interval of concurrent record during which the spatial correlation was effective. In this analysis, the effective spatial correlation was computed as a function of the residuals ζ of the basin-specific estimates of annual ground-water discharge rather than the annual ground-water discharges (q) themselves. The residuals were used because the autocorrelation characteristics of the annual ground-water discharge series may have resulted in overestimation of the spatial correlation structure. The form of the equation used to estimate the effective spatial correlation was

$$\rho(\zeta_i, \zeta_j) = \frac{m_{ij}\hat{\rho}_{ij}}{\sqrt{n_i n_j}}, \tag{9}$$

where

m_{ij} is the concurrent record length between stations i and j,

$\hat{\rho}_{ij}$ is a smooth, monotonically decreasing function of the separation distance, d_{ij}, between corresponding basin centroids, and

n_i and n_j are the number of years of record at the ith and jth stations, respectively.

The form of the nonlinear equation used to estimate $\hat{\rho}_{ij}$ was

$$\hat{\rho}_{ij} = \beta_0^{\left[\frac{d_{ij}}{\beta_1 d_{ij}+1}\right]}, \qquad (10)$$

where β_0 and β_1 are estimated regression coefficients determined by use of a weighted least-squares (WLS) analysis.

Preliminary estimates of coefficients associated with equation 6 were computed by use of WLS analysis (SAS Institute, 1989, p. 1385). The preliminary estimates were necessary for efficient evaluation of many alternative equations initially considered. The weights for each observation were equal to the reciprocal of the variances of the basin-specific recharge estimates and were used to estimate a coefficient vector as

$$\vec{\beta}_{WLS} = [\underline{X}'[\vec{S}^2 \underline{I}_n]^{-1}\underline{X}]^{-1}\underline{X}'[\vec{S}^2 \underline{I}_n]^{-1}\vec{y} \ , \qquad (11)$$

where S is the variance associated with recharge estimates at each of the n gaging stations.

Final estimates of coefficients for equation 6 were obtained by use of the generalized least-squares (GLS) procedure (Tasker and Stedinger, 1989). The GLS procedure accounts not only for the differences in variances of basin-specific recharge estimates but also for the cross-correlation of concurrent flows at other gaging stations. The GLS estimates of regression-model coefficients β_{GLS} are determined by iteratively solving

$$\vec{\beta}_{GLS} = [\underline{X}'\underline{\Lambda}^{-1}\underline{X}]^{-1}\underline{X}'\underline{\Lambda}^{-1}\vec{y} \qquad (12)$$

and

$$[\vec{y} - \underline{X}\vec{\beta}_{GLS}]'\underline{\Lambda}^{-1}[\vec{y} - \underline{X}\vec{\beta}_{GLS}] = n - p \qquad (13)$$

(Tasker and Stedinger, 1989, p. 365).

Once the solution to equations 12 and 13 was obtained, the estimated covariance of β_{GLS} was computed as $[\underline{X}'\underline{\Lambda}^{-1}\underline{X}]^{-1}$. This matrix, together with the model-error variance, was used to calculate the relative uncertainty of the estimated recharge for a basin with characteristics $\vec{x}$ as

$$s_{y_{GLS}} = \sqrt{\vec{x}'[\underline{X}'\underline{\Lambda}^{-1}\underline{X}]^{-1}\vec{x} + \hat{\gamma}^2} \ . \qquad (14)$$

ANNUAL GROUND-WATER COMPONENTS OF STREAMFLOW

Annual ground-water discharges differed widely among selected stations (figs. 7–10). Among the 3,456

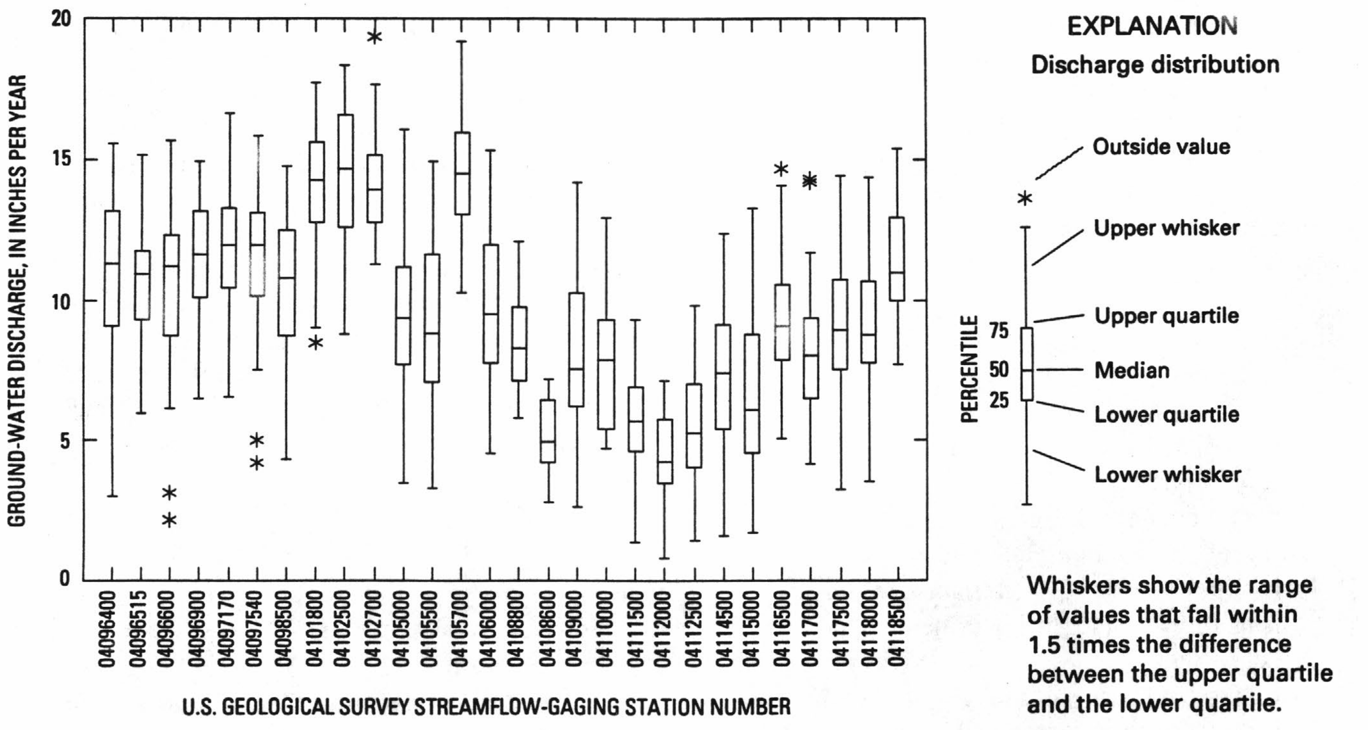


Figure 7. Distribution of annual rates of ground-water discharge in Zone A, Lower Peninsula of Michigan.

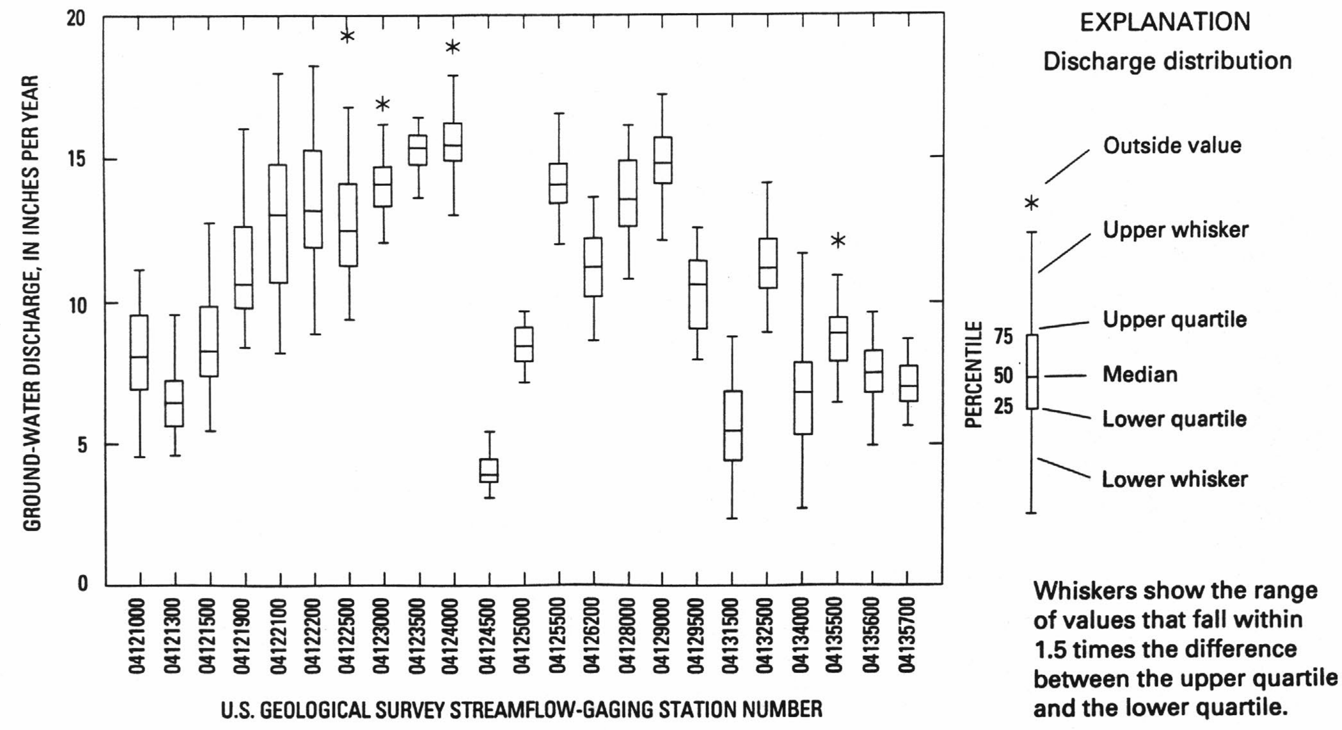


Figure 8. Distribution of annual rates of ground-water discharge in Zone B, Lower Peninsula of Michigan.

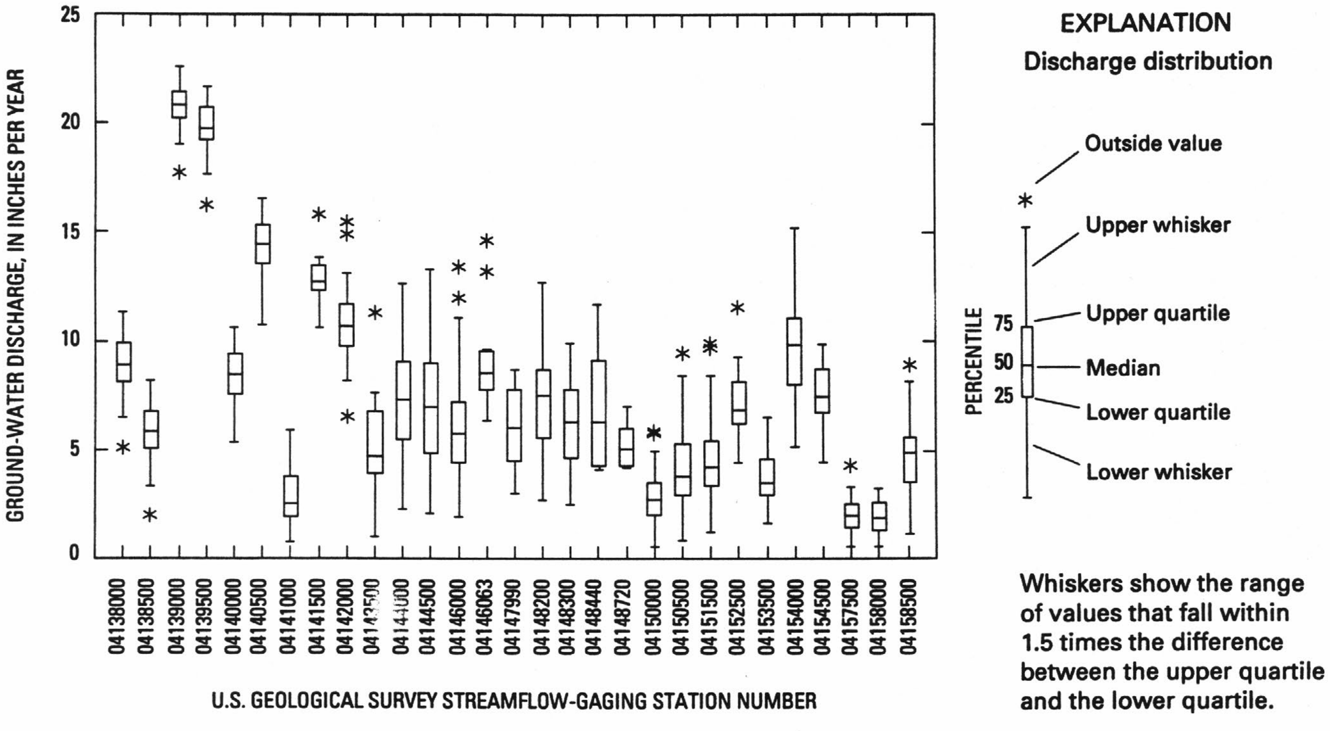


Figure 9. Distribution of annual rates of ground-water discharge in Zone C, Lower Peninsula of Michigan.

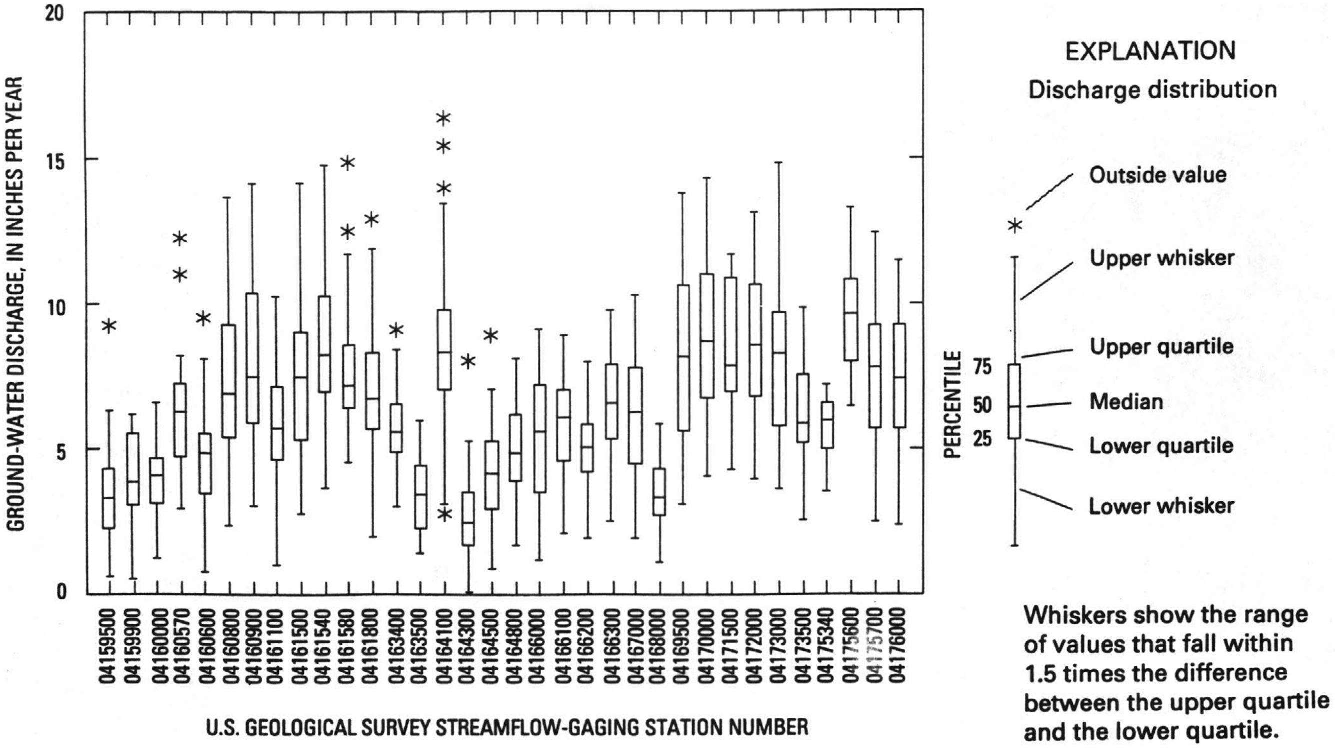


Figure 10. Distribution of annual rates of ground-water discharge in Zone D, Lower Peninsula of Michigan.

station-years of daily streamflow data analyzed, the annual ground-water discharge ranged from a minimum of 0.19 in/yr in 1964 at East Branch Coon Creek at Armada, Mich. (USGS gaging station 04164300), to a maximum of 22.7 in/yr in 1967 at Houghton Creek near Lupton, Mich. (USGS gaging station 04139000). The average ground-water discharge for these records is 8.41 in/yr; the standard deviation is 4.09 in/yr. In this report, annual ground-water discharges are expressed in areal inches that were computed by dividing flow volumes by drainage areas determined on the basis of surface topographic features.

The average percentage of streamflow identified as ground-water discharge also differed widely among selected gaging stations (fig. 11). Columbia Drain near Sebewaing, Mich. (USGS gaging station 04158000), had the smallest average annual ground-water component, 29.6 percent; Manistee River near Grayling, Mich. (USGS gaging station 04123500), had the largest average ground-water component, 97.0 percent.

Variations in ground-water discharge result from temporal and spatial differences in climatic characteristics and from spatial differences in basin characteristics. To determine the spatial relation of climatic

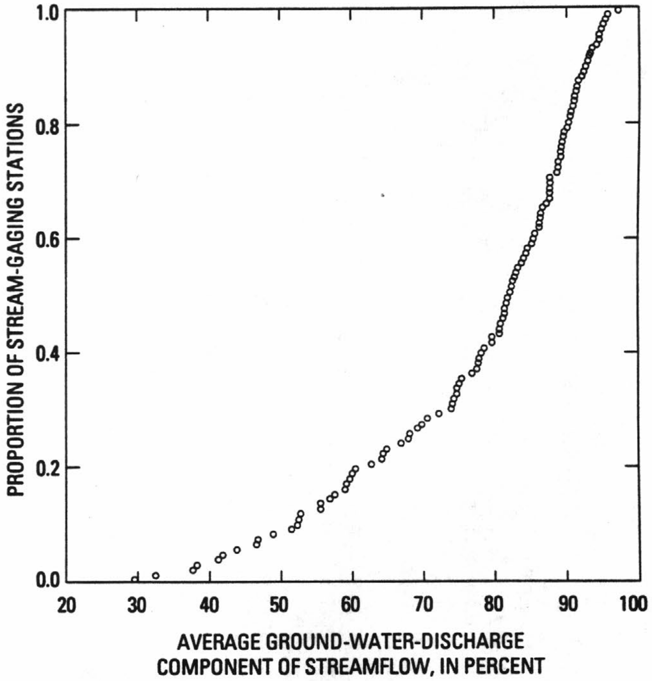


Figure 11. Distribution of the ground-water-discharge component of streamflow in the Lower Peninsula of Michigan.

factors and basin characteristics to recharge, the temporal variations in recharge were removed by use of the basin-specific dynamic regression equations discussed in the following section.

NORMAL BASIN RECHARGE RATES

A set of basin-specific regression equations (using variables in table 2) was developed to relate annual variations in ground-water discharge to annual variations in precipitation and the previous year's ground-water discharge. The general form of these equations is equation 1. Annual mean precipitation values, $p_{i,j}$, were computed as the weighted-average annual precipitation of the three closest precipitation stations to the *i*th basin centroid operated during the *j*th year. Weights were inversely proportional to the squared distance between the basin centroids and the precipitation stations. Normal basin precipitation, p_{in}, was computed similarly by use of 107 precipitation stations distributed throughout the Lower Peninsula for which normal precipitation was available (Fred Nurnberger, State Climatologist, Michigan Department of Agriculture, written commun., 1992).

Normal basin recharge rates were generally computed by use of the steady-state form (eq. 3) of the basin-specific regression equations. Of the 114 basin-specific equations, 72 included coefficients associated with both annual precipitation and the previous year's ground-water discharge component, 34 included coefficients associated with precipitation but not the previous year's annual ground-water component, and 2 equations included coefficients associated with the previous year's annual ground-water component but not the annual precipitation. All equations contained an intercept term. Only coefficients significant at the 5-percent level were maintained in the equations; thus, for six stations, the basin recharge rate was based on the base flow.

All coefficients associated with either annual precipitation or the previous year's ground-water discharge component were positive. The positive coefficients are consistent with the assumed physical relations among precipitation, aquifer storage, and ground-water discharge. The equations explained from 18.6 to 75.8 percent of the variation in annual ground-water discharges. In general, the normal recharge rates closely matched the corresponding average ground-water discharges (fig. 12). Over all selected basins, the average ground-water discharge was 0.24 in/yr higher than the normal recharge rate.

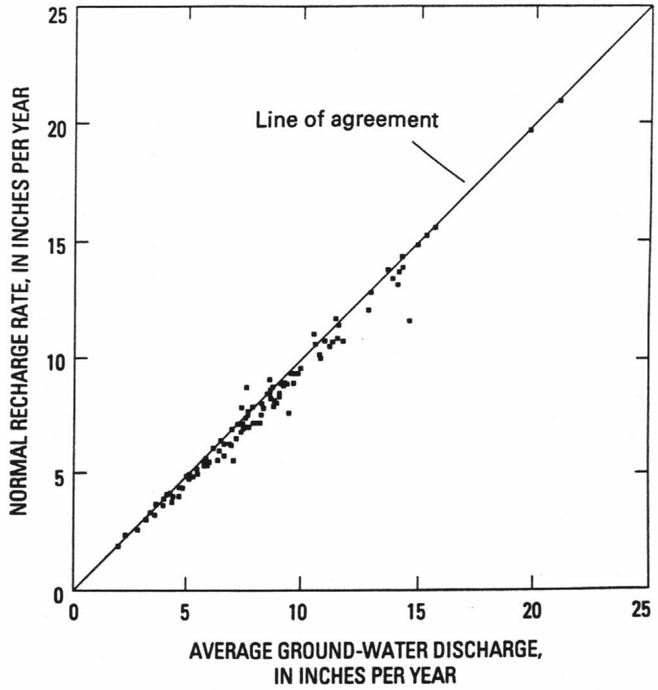


Figure 12. Relation between average ground-water discharge and corresponding normal recharge rates, Lower Peninsula of Michigan.

The validity of the basin-specific regression equations and the corresponding normal-recharge-rate estimates is dependent upon satisfying the assumptions concerning the residual terms (ζ_i). The standard assumptions include stationarity (constant mean and variance), normality, and independence. No stations were identified that violated the standard assumptions on the basis of statistical analyses of the residuals.

A GENERALIZED ESTIMATE OF RECHARGE RATES

A regression equation was developed to provide a generalized estimate of recharge. The equation is a multiple-linear-regression equation that describes the statistical relation between normal recharge rates and selected basin characteristics. Development of this equation required (1) identification of appropriate basin characteristics for use as explanatory variables in the equation, (2) estimation of coefficients associated with the selected characteristics, (3) evaluation of the regression equation by comparison of normal basin recharge rates with estimates based on the regression equation, and (4) computation of the generalized estimate of recharge to depict the spatial variation of

Table 2. Normal basin recharge rates at selected streamflow gaging stations, Lower Peninsula of Michigan

[USGS, U.S. Geological Survey; NA indicates that an entry is not applicable on the basis of the regression analysis]

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Average basin recharge rate (inches per year)	Normal basin recharge rate (inches per year) y_i	Standard error of the mean (inches) S_i	Coefficient β_0	Coefficient β_1	Normal precipitation (inches per year) p_{iN}	Coefficient β_2	Coefficient of determination R^2	Root-mean-square error (inches) s_i	Years of record n_i–1
A	1	04096400	11.17	10.66	0.4188	−6.736	0.3541	36.1	0.4326	0.518	2.072	27
A	2	04096515	10.66	9.99	.4473	−10.23	.4657	36.1	.3427	.523	1.900	20
A	3	04096600	10.64	10.10	.4388	−7.449	.4142	33.9	.3480	.538	2.128	25
A	4	04096900	11.41	10.80	.4727	2.096	.260	33.5	NA	.186	1.981	24
A	5	04097170	11.36	11.36	.5653	NA	NA	NA	NA	NA	2.190	15
A	6	04097540	11.63	10.70	.2992	−6.473	.3936	33.6	.3693	.691	1.416	27
A	7	04098500	10.39	11.00	.4450	−4.581	.2883	34.1	.5219	.644	1.695	16
A	8	04101800	14.04	13.66	.2113	−3.083	.2667	37.2	.4990	.758	1.104	29
A	9	04102500	14.19	13.86	.2718	−3.232	.2500	37.5	.5562	.642	1.658	38
A	10	04102700	13.98	13.12	.2508	.687	.3305	37.6	NA	.718	1.075	23
A	11	04105000	9.78	9.48	.2637	−5.506	.3338	32.4	.4388	.529	1.951	56
A	12	04105500	9.22	8.80	.2528	−3.928	.2781	32.5	.4181	.549	1.782	52
A	13	04105700	14.51	11.55	.4539	−7.226	.3606	33.9	.5676	.714	1.141	24
A	14	04106000	9.54	9.27	.2171	−4.802	.2956	33.0	.4658	.653	1.520	50
A	15	04108600	8.62	7.83	.3858	.317	.2218	33.9	NA	.252	1.403	25
A	16	04108800	5.06	4.90	.1947	−.884	.1638	36.3	NA	.357	.920	30
A	17	04109000	6.79	6.21	.2722	−7.145	.3422	30.4	.4731	.529	1.805	48
A	18	04110000	7.73	7.15	.7108	−3.153	.3437	30.0	.3437	.325	2.218	11
A	19	04111500	5.75	5.58	.2000	−2.802	.2131	30.4	.3428	.525	1.171	35
A	20	04112000	4.54	4.41	.2039	−2.535	.1841	30.8	.2896	.436	1.197	35
A	21	04112500	5.63	5.52	.1728	−4.886	.2505	30.7	.4898	.581	1.322	59
A	22	04114500	7.40	6.99	.2987	−6.828	.3710	30.0	.3859	.525	1.965	45
A	23	04115000	6.69	6.24	.2914	−5.834	.4037	29.9	NA	.507	1.926	46
A	24	04116500	9.35	9.28	.2718	−4.621	.2884	33.0	.4720	.553	1.581	34
A	25	04117000	8.42	9.03	.3834	−2.454	.1542	32.7	.7139	.651	1.636	20
A	26	04117500	9.14	8.86	.2782	−4.683	.3063	32.2	.4166	.546	1.845	45
A	27	04118000	9.07	8.76	.2899	−4.042	.2695	32.0	.4782	.617	1.692	35
A	28	04118500	11.47	11.36	.2906	−2.574	.2665	33.2	.4880	.518	1.580	30
B	29	04121000	8.11	8.00	.3098	−4.612	.3110	30.5	.3924	.367	1.574	26
B	30	04121300	6.50	6.29	.2144	1.798	.1473	30.5	NA	.343	1.010	24
B	31	04121500	8.47	8.43	.1549	−1.647	.2864	29.3	.2007	.505	1.158	56
B	32	04121900	11.05	10.47	.2731	1.734	.2748	31.8	NA	.584	1.211	23
B	33	04122100	12.74	12.03	.4955	−2.873	.3311	31.9	.3617	.355	2.245	24
B	34	04122200	13.76	13.38	.3327	2.119	.2051	33.7	.3256	.397	1.812	32

Table 2. Normal basin recharge rates at selected streamflow gaging stations, Lower Peninsula of Michigan—Continued

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Average basin recharge rate (inches per year)	Normal basin recharge rate (inches per year) y_i	Standard error of the mean (inches) S_i	Coefficient β_0	Coefficient β_1	Normal precipitation (inches per year) p_{iN}	Coefficient β_2	Coefficient of determination R^2	Root-mean-square error (inches) s_i	Years of record n_i–1
B	35	04122500	12.84	12.76	0.2001	–0.906	0.2254	33.7	0.4753	0.600	1.411	50
B	36	04123000	14.19	14.34	.1765	3.373	.1910	31.4	.3468	.370	.949	30
B	37	04123500	15.23	15.24	.0909	2.986	.1351	32.8	.5133	.565	.498	30
B	38	04124000	15.59	15.61	.1210	6.253	.1343	31.1	.3314	.327	.906	56
B	39	04124500	4.14	4.14	.2248	NA	NA	NA	NA	NA	NA	10
B	40	04125000	8.55	8.69	.6522	4.883	.1248	30.5	NA	.367	.619	10
B	41	04125500	14.14	14.32	.1958	3.476	.1365	31.3	.4588	.360	.982	27
B	42	04126200	11.30	11.38	.2287	1.056	.1779	33.2	.3883	.424	.925	17
B	43	04128000	13.57	13.75	.1010	–1.716	.1717	33.2	.7098	.778	.685	47
B	44	04129000	14.86	14.83	.1242	2.726	.1744	32.1	.4389	.551	.765	38
B	45	04129500	10.43	10.52	.1373	–.902	.2496	30.9	.3519	.583	.832	37
B	46	04131500	5.63	5.39	.2511	–6.661	.3988	30.2	NA	.500	1.259	26
B	47	04132500	11.32	11.65	.2054	1.231	.2124	28.0	.3836	.445	.970	26
B	48	04134000	6.80	6.91	.2949	–4.302	.3858	29.1	NA	.372	1.714	34
B	49	04135500	8.85	8.47	.0983	–2.067	.1550	32.5	.6493	.674	.618	47
B	50	04135600	7.51	7.52	.1733	–1.812	.1413	32.3	.6344	.412	.848	24
B	51	04135700	7.09	7.10	.1443	.702	.2032	31.5	NA	.365	.677	22
C	52	04138000	8.92	8.88	.2850	3.595	.1851	28.6	NA	.207	1.365	23
C	53	04138500	5.73	5.73	.2233	.110	.1942	28.9	NA	.215	1.223	30
C	54	04139000	20.97	20.9	.1238	15.44	.1895	28.8	NA	.544	.596	20
C	55	04139500	19.73	19.7	.2229	12.66	.2427	29.0	NA	.469	.996	20
C	56	04140000	8.37	8.42	.2200	–2.504	.2785	28.9	NA	.553	1.007	21
C	57	04140500	14.24	14.31	.1788	3.165	.2262	29.0	NA	.398	.975	30
C	58	04141000	2.73	2.60	.1873	1.669	NA	NA	.3576	.172	.867	24
C	59	04141500	12.87	12.9	.3386	6.978	.2065	28.8	NA	.325	1.120	11
C	60	04142000	10.85	10.7	.1845	2.134	.2090	28.9	.2346	.323	1.320	53
C	61	04143500	5.00	5.00	.3044	–.417	.1912	28.4	NA	.133	1.639	29
C	62	04144000	7.34	6.91	.2561	–4.543	.2784	30.3	.4353	.672	1.459	34
C	63	04145000	7.04	6.50	.2089	–5.973	.3366	29.2	.4093	.730	1.345	44
C	64	04146000	6.22	5.57	.2284	–4.507	.2727	28.0	.4376	.762	1.613	56
C	65	04146063	9.31	7.58	.9634	–4.221	.4217	28.0	NA	.367	2.120	10
C	66	04147990	6.07	6.07	.5524	NA	NA	NA	NA	NA	2.026	14
C	67	04148200	7.22	7.85	.4582	–3.368	.2338	29.6	.5461	.532	1.844	18
C	68	04148300	6.73	6.29	.3226	–2.341	.1991	29.4	.4402	.772	.985	12
C	69	04148440	6.91	5.58	.5322	–5.779	.3077	28.8	.4488	.594	1.577	13

Table 2. Normal basin recharge rates at selected streamflow gaging stations, Lower Peninsula of Michigan—Continued

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Average basin recharge rate (inches per year)	Normal basin recharge rate (inches per year) y_i	Standard error of the mean (inches) S_i	Coefficient β_0	Coefficient β_1	Normal precipitation (inches per year) p_{iN}	Coefficient β_2	Coefficient of determination R^2	Root-mean-square error (inches) s_i	Years of record n_i–1
C	70	04148720	5.23	4.90	0.2726	1.241	0.1271	28.8	NA	0.275	0.885	14
C	71	04150000	3.10	3.05	.2214	−1.211	.1508	28.3	NA	.241	1.230	31
C	72	04150500	4.21	3.81	.2106	−2.809	.2006	28.4	0.2430	.447	1.292	42
C	73	04151500	4.55	4.06	.1814	−3.596	.2407	27.8	.2348	.551	1.175	48
C	74	04152500	7.43	7.40	.2426	2.370	.1636	30.7	NA	.359	1.028	18
C	75	04153500	3.85	3.96	.2075	−.151	.1354	30.3	NA	.144	1.221	36
C	76	04154000	9.67	9.30	.2780	−1.440	.3524	30.5	NA	.602	1.413	27
C	77	04154500	7.55	7.63	.2585	2.574	.1675	30.2	NA	.227	1.284	25
C	78	04157500	2.20	2.37	.2274	1.081	NA	NA	.5431	.303	.817	14
C	79	04158000	1.89	1.89	.2038	NA	NA	NA	NA	NA	.815	16
C	80	04158500	4.83	4.90	.2877	−2.894	.2228	28.5	.2950	.339	1.513	28
D	81	04159500	3.31	3.31	.1987	NA	NA	NA	NA	NA	1.333	45
D	82	04159900	4.00	4.12	.3214	−3.312	.2611	28.5	NA	.450	1.195	14
D	83	04160000	3.84	3.67	.2505	−1.722	.1879	28.7	NA	.538	.989	16
D	84	04160570	6.49	5.77	.3598	−2.738	.2272	28.3	.3616	.407	1.541	24
D	85	04160600	4.71	4.40	.2765	−2.694	.2489	28.5	NA	.440	1.421	28
D	86	04160800	7.58	6.99	.3683	−5.958	.3613	29.2	.3437	.568	1.951	30
D	87	04160900	8.07	7.50	.3356	−5.626	.3146	29.3	.5208	.630	1.782	30
D	88	04161100	5.77	5.33	.2291	−4.525	.2603	29.3	.4201	.694	1.217	30
D	89	04161500	7.43	8.67	.5239	−3.796	.2092	29.0	.7375	.588	1.897	19
D	90	04161540	8.67	8.11	.3498	−3.938	.2858	29.1	.4606	.558	1.847	30
D	91	04161580	8.05	7.15	.4326	−2.935	.2485	28.6	.4158	.438	1.896	25
D	92	04161800	7.22	6.77	.2947	−3.971	.2631	28.8	.4678	.633	1.603	31
D	93	04163400	5.76	5.37	.2504	−1.055	.2193	29.3	NA	.425	1.168	25
D	94	04163500	3.52	3.69	.2955	−1.977	.1938	29.2	NA	.548	1.012	12
D	95	04164100	8.78	8.02	.3546	−5.299	.3338	28.5	.4735	.682	1.902	31
D	96	04164300	2.75	2.58	.2400	−2.378	.1716	28.9	NA	.277	1.333	32
D	97	04164500	4.33	4.01	.1735	−3.158	.2066	28.7	.3114	.599	1.094	42
D	98	04164800	5.31	5.21	.3223	−1.928	.1696	28.9	.4290	.604	1.071	15
D	99	04166000	5.34	5.03	.2081	−4.270	.2169	29.5	.5781	.671	1.281	39
D	100	04166100	5.88	5.55	.2034	−3.775	.2105	29.7	.5535	.715	1.111	31
D	101	04166200	5.00	4.78	.1770	−1.664	.1447	30.1	.4382	.569	.968	31
D	102	04166300	6.27	6.03	.2179	−2.790	.1814	30.3	.5506	.626	1.194	31
D	103	04167000	6.25	5.97	.2175	−4.284	.2065	30.8	.6525	.689	1.248	35
D	104	04168000	3.51	3.25	.1223	−2.209	.1363	30.9	.3829	.546	.758	42

Table 2. Normal basin recharge rates at selected streamflow gaging stations, Lower Peninsula of Michigan—Continued

Zone (fig. 1)	Station identification (figs. 2–5)	USGS gaging station number	Average basin recharge rate (inches per year)	Normal basin recharge rate (inches per year) y_i	Standard error of the mean (inches) S_i	Coeffi-cient β_0	Coeffi-cient β_1	Normal precip-itation (inches per year) p_{iN}	Coeffi-cient β_2	Coeffi-cient of deter-mination R^2	Root-mean-square error (inches) s_i	Years of record n_i–1
D	105	04169500	8.15	7.76	0.3375	–5.748	0.3117	29.8	0.5434	0.682	1.732	27
D	106	04170000	8.87	8.28	.2626	–5.408	.3105	30.3	.5166	.637	1.622	41
D	107	04171500	8.50	8.56	.4342	–.314	.2829	31.4	NA	.509	1.736	16
D	108	04172000	8.52	8.20	.2776	–2.985	.2390	31.2	.4545	.497	1.680	38
D	109	04173000	7.85	7.18	.3238	–4.122	.2671	31.1	.4149	.706	1.495	24
D	110	04173500	6.31	6.44	.2469	–2.321	.1657	30.3	.5796	.506	1.313	29
D	111	04175340	5.69	5.69	.3882	NA	NA	NA	NA	NA	1.288	11
D	112	04175600	9.48	8.87	.4613	–2.297	.3488	32.0	NA	.331	1.706	17
D	113	04175700	7.69	7.87	.3771	–3.875	.2408	31.8	.5196	.570	1.759	22
D	114	04176000	7.28	7.14	.2737	–3.613	.2206	32.7	.4954	.608	1.442	28

recharge rates in the Lower Peninsula. The results of these analyses are discussed in the following sections.

Identifying an Equation for Recharge Estimation

Model identification is a process of selecting an appropriate subset of the available basin-characteristics data for use as explanatory variables in a regression equation. Preliminary selection of basin characteristics was guided by automated model-selection techniques including the STEPWISE method and the RSQUARE method (SAS Institute, 1989, p. 1398). Automated techniques are efficient and appropriate for preliminary evaluation of a large number of alternative equations.

Final model identification was based on physical reasoning and on an iterative analysis of alternative equations. In general, the preferred equations (1) included basin characteristics that are found within most basins, (2) satisfied implicit constraints on coefficients or sets of coefficients based on considerations associated with the physical process, and (3) explained a high proportion of the variability in basin recharge with few model coefficients. Model simplicity and consistency with physical processes were critical in model selection because of the need to apply the model across the Lower Peninsula. Therefore, only the main effects of explanatory variables were included in the selected equation. Higher order terms, such as powers of explanatory variables or interaction terms among explanatory variables, were not included. Similarly, local effects of human activity could not be identified with the available information.

Effects of individual observations (stations) on the selection of basin characteristics also were scrutinized. Preliminary modeling indicated that regression estimates of recharge for three stations in the upper Rifle River Basin (Houghton Creek near Lupton, Mich., USGS gaging station 04139000; Rifle River near Lupton, Mich., USGS gaging station 04139500; and Prior Creek near Selkirk, Mich., USGS gaging station 04140000) were smaller than the normal basin recharge estimates. Similarly, the regression estimate of recharge for a gaging station in an adjacent basin (South Branch Au Sable River near Luzerne, Mich., USGS gaging station 04135700) was greater than the value indicated by streamflow partitioning.

Investigation of this discrepancy revealed that an interbasin transfer of water had been documented in

Table 3. Statistics describing the distribution of selected explanatory variables

Explanatory variable[1]	Mean	Standard deviation	Minimum	Lower quartile	Median	Upper quartile	Maximum
SLAT	0.0000	1.0000	−1.5959	−0.6911	−0.3346	0.6247	2.3872
SLON	.0000	1.0000	−1.5339	−.9303	−.1001	.7968	2.0505
SGOSAND	.2580	.2136	.0000	.0714	.2143	.4299	.7603
SGCTIL	.0751	.1455	.0000	.0000	.0012	.0919	.9615
LUFD	.2064	.1659	.0000	.0574	.1862	.3286	.6615
LUFC	.0370	.0845	.0000	.0000	.0000	.0000	.3594

[1]Variables are defined and discussed on p. 22.

this area (Knutilla and others, 1971, p. 41). The interbasin transfer occurs because the surface-water and ground-water boundaries are not coincident. In this case, some precipitation that falls within the South Branch Au Sable River Basin, as defined by the surface topographic features, is transferred to the upper Rifle River Basin because of the natural ground-water flow gradient. Because of the possible differences between the location of the surface-water and ground-water divides in the four identified basins, the drainage areas needed to adjust streamflow volumes could not be determined with confidence. Therefore, to reduce the effect of this uncertainty on the recharge equation, the four identified gaging stations were removed from the set used to estimate coefficients for the recharge equation.

On the basis of available basin-characteristics data that included climatic, physiographic, geologic, geographic, and land-use classification indices, six characteristics were selected for use as explanatory variables. Selected geographic indices include the latitude and longitude of the basin centroids. The remaining four variables describe the proportion of the basins covered by the surficial geologic material classified as glacial-outwash sand and gravel and postglacial alluvium (SGOSAND); the surficial geologic material classified as coarse-textured glacial till (SGCTIL); the land-use classification of deciduous forests (LUFD); and the land-use classification of coniferous forests (LUFC).

Latitude and longitude of the basin centroids are thought to be associated with the continuous variation of recharge with climatic factors. The selected geologic indices, which include primarily coarse-grained materials, would likely be associated with higher average recharge rates than other geologic indices because coarse-grained materials allow faster infiltration of water than fine-grained materials do. Similarly, forested lands would likely be associated with higher recharge rates than most other land-use classifications because of higher infiltration rates. Infiltration rates are maintained in forested areas because leaf litter generally protects the infiltration capacities of soils and because the soils are infrequently exposed to mechanical compaction that can reduce infiltration capacities.

Latitudes and longitudes of basin centroids were standardized before analysis to clarify the effect of the basin geographic variables and the model intercept term on recharge estimates. Standardization was done by replacing the latitude of the *i*th basin centroid, LAT_i, with $SLAT_i$ defined as $(LAT_i - \text{mean}(LAT))/\text{std}(LAT)$, where the mean(LAT) is the mean latitude (43.1636 degrees) of the basin centroids used in the analysis and std(LAT) is the standard deviation (0.8908 degrees) of the latitudes of basin centroids used in the analysis. The standardized longitude, SLON, was defined similarly. The mean longitude equals 84.2476 degrees, and the standard deviation of the longitudes equals 0.9444 degrees.

A statistical summary of the distributional characteristics of the explanatory variables is given in table 3. The standardized latitude and longitude are approximately symmetrically distributed with a mean of 0 and a standard deviation of 1. The four remaining characteristics are from a mixed probability distribution model having a positive probability mass at 0 and continuous distributions above that point to a theoretical maximum value of 1. The spatial distributions of the selected surficial geologic materials and forest types are shown on figures 13 and 14.

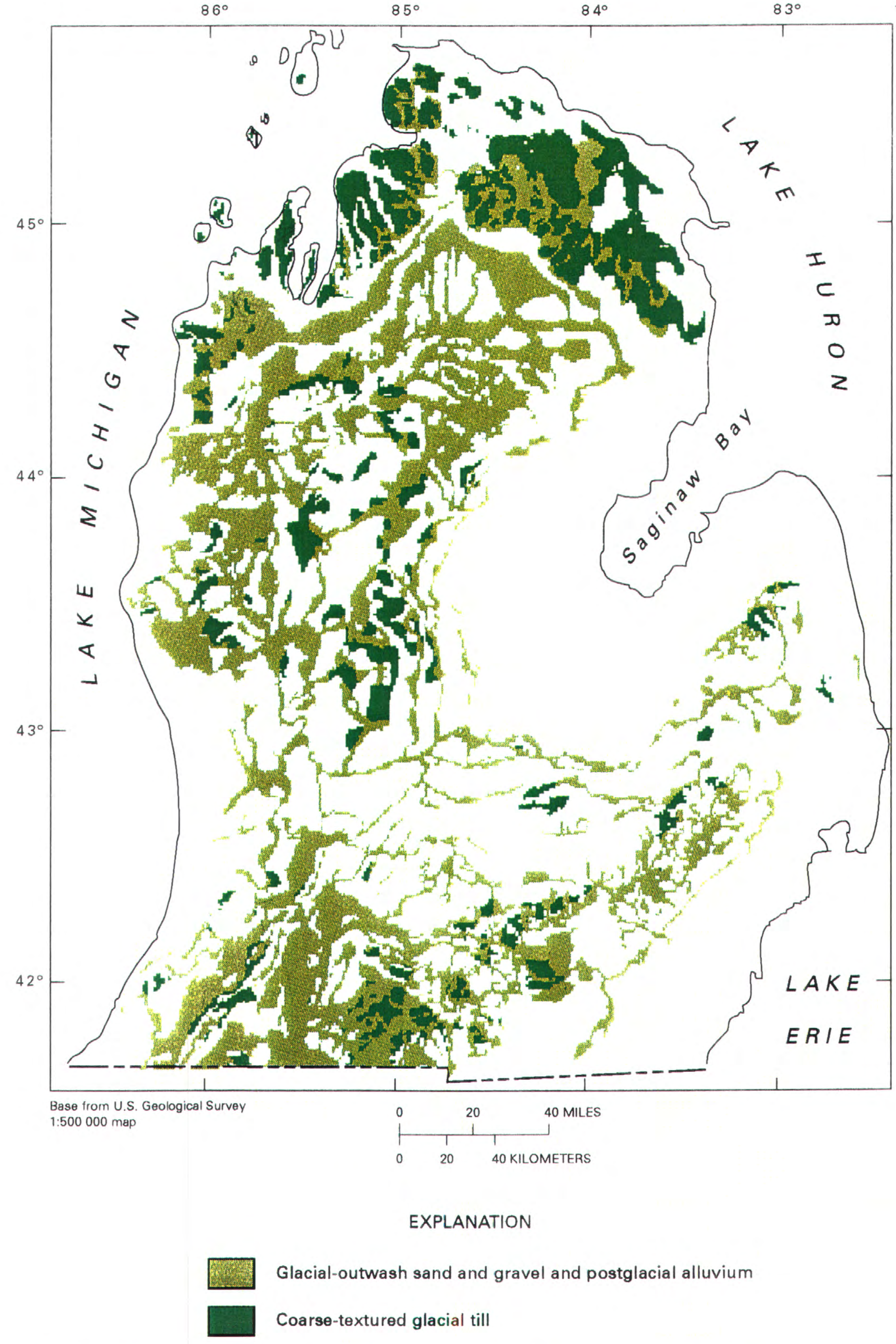


Figure 13. Distribution of selected surficial geologic materials in the Lower Peninsula of Michigan.

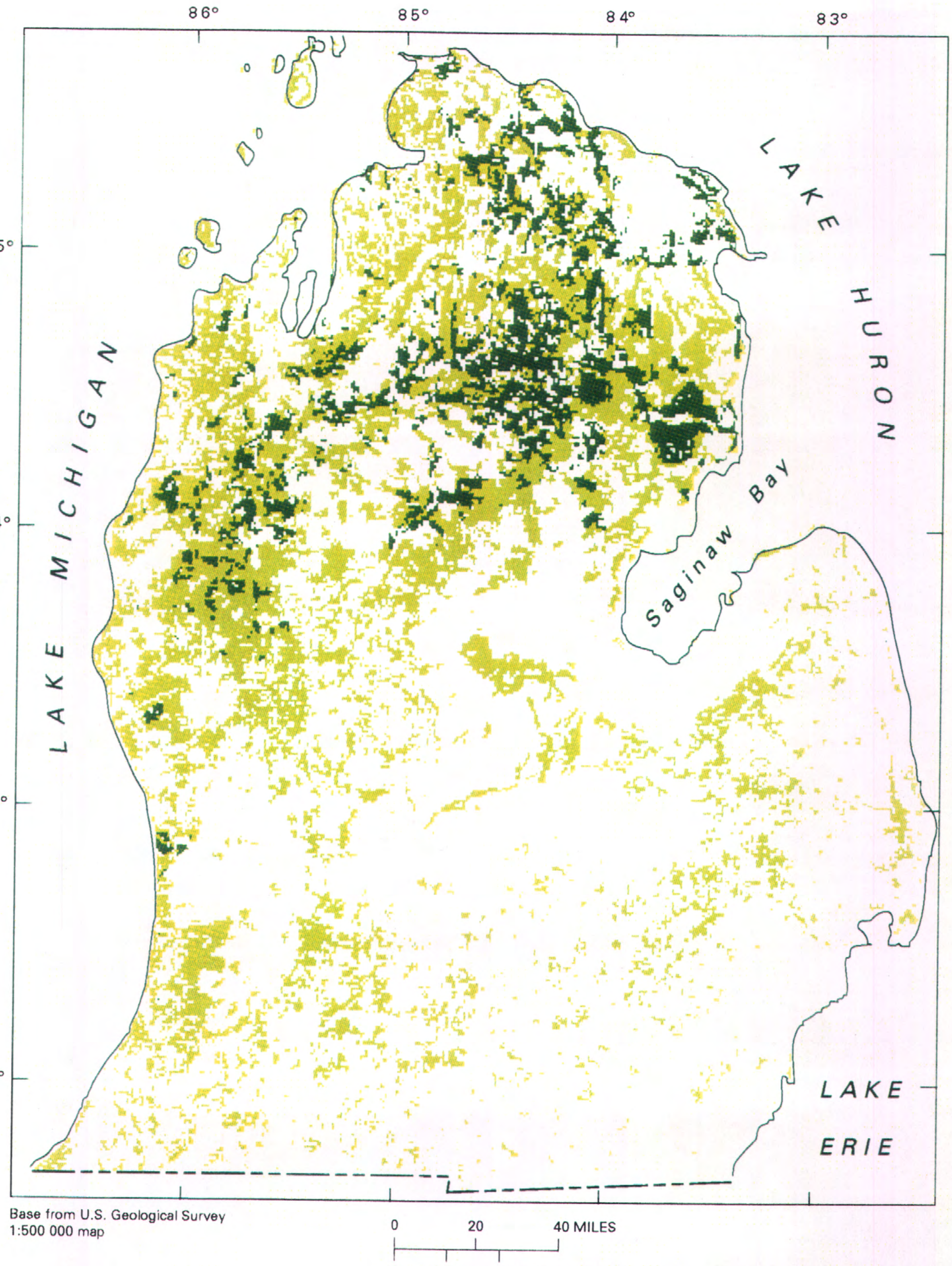


Figure 14. Distribution of land classified as forest in the Lower Peninsula of Michigan.

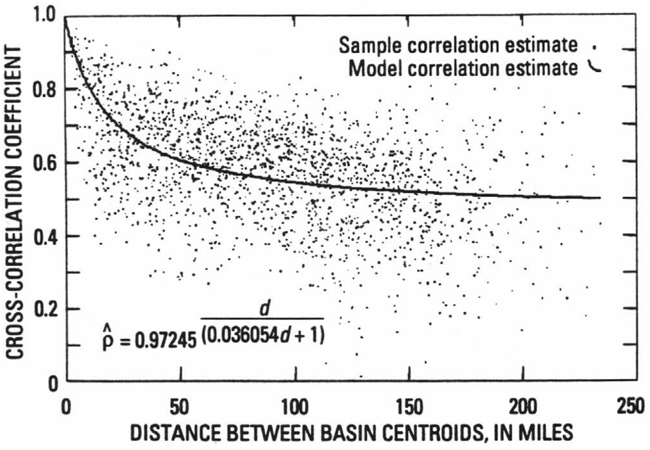


Figure 15. Spatial correlation structure of residuals from the analysis of annual ground-water-discharge rates in the Lower Peninsula of Michigan. See equation 10.

Estimating Coefficients for the Recharge Equation

Model identification was based on preliminary estimates of coefficients determined by use of weighted least-square estimates (WLS) (eq. 11); however, the WLS estimates of regression coefficients are based on the assumption that cross-correlation between adjacent basins is zero. To verify the adequacy of this assumption, sample estimates of cross-correlation were computed between 2,994 residuals of the basin-specific regression equations with 20 or more years of concurrent record. Inspection of the distribution of the sample estimates indicates a gradual decrease in cross-correlation with increasing separation distance from a maximum of about 1 at no separation distance to a minimum of about 0.5 at a separation distance of 250 mi (fig. 15). Because the sample estimates are not distributed with a mean of zero for nonzero separation distances, the use of a WLS was inappropriate for final estimation. Therefore, final coefficient estimates for the identified model were computed by use of the generalized least-squares (GLS) method.

Determination of the GLS estimates required estimation of the $\hat{\underline{\Sigma}}$ matrix (eq. 8) and the iterative solution of equations 12 and 13. In this analysis, the square $\hat{\underline{\Sigma}}$ matrix was of order 110. The principal diagonal components were initially estimated on the basis of the standard error of the basin-specific recharge estimates (eq. 4).

Data from five stations were identified as strongly influencing the coefficient estimates on the basis of standard regression diagnostics (Belsley and others, 1980, p. 27). The influential stations were (1) Manistee River near Grayling, Mich. (USGS gaging station 04123500), (2) Manistee River near Sherman, Mich. (USGS gaging station 04124000), (3) Sturgeon River near Wolverine, Mich. (USGS gaging station 04128000), (4) Pigeon River near Vanderbilt, Mich. (USGS gaging station 04129000), and (5) Au Sable River at Grayling, Mich. (USGS gaging station 04135500). To avoid possible degradation of regression-coefficient estimates, the initial estimates for the diagonal components corresponding to these five stations were replaced with the median value of the diagonal components from the remaining stations. The off-diagonal elements of the $\hat{\underline{\Sigma}}$ matrix were estimated on the basis of basin-specific standard errors and spatial correlation structure. Model estimates of the spatial correlation structure were used rather than sample estimates to ensure solution of equations 12 and 13.

The sample cross-correlation data were fitted to equation 10 by nonlinear WLS analysis, where the weights were proportional to the length of concurrent record. The model correlation estimate approximates the spatial correlation as a monotonically decreasing function with increasing basin-separation distance. The function ranges from a maximum of 1 to a minimum of 0.46 for all stations in Michigan (fig. 15). Coefficient estimates for the spatial correlation function (β_0, β_1) are 0.97245 and 0.036054, and asymptotic standard errors are 0.0014796 and 0.002611, respectively.

Coefficient estimates for the recharge equation, determined by use of WLS and GLS techniques, were consistent in sign and similar in magnitude (table 4). The coefficient associated with SLON increased the most (18.9 percent); the coefficient associated with SGCTIL decreased the most (–29.9 percent). Only the coefficient associated with SGCTIL dropped below the nominal 0.05 level of significance as a result of the change in estimation techniques. However, because the GLS estimate of the coefficient maintained at least a 0.10 level of significance, the corresponding explanatory variable was not removed from the recharge equation.

In addition to GLS coefficient estimates, solution of equations 12 and 13 provides estimates of the covariance among the coefficients (table 5) and the model-error variance ($\hat{\gamma}^2$ = 3.0564 in^2). These values were used to compute the relative uncertainty of prediction for the estimated recharge rates by use of equation 14.

Table 4. Coefficient estimates for variables used in the recharge equation for the Lower Peninsula of Michigan
[$\hat{y} = \beta_0 + \beta_1\mathrm{SLAT} + \beta_2\mathrm{SLON} + \beta_3\mathrm{SGOSAND} + \beta_4\mathrm{SGCTIL} + \beta_5\mathrm{LUFD} + \beta_6\mathrm{LUFC}$]

Explanatory variable[1]	Coefficient	Estimation method[2]	Coefficient estimate	Estimated standard error	Test statistic for the null hypothesis that the coefficient equals 0	Probability that the coefficient is equal to 0
Intercept	β_0	WLS[2]	4.33484	0.36355	11.924	0.0001
	β_0	GLS[3]	4.86592	.40035	12.154	.0001
SLAT	β_1	WLS	−1.15490	.28771	−4.014	.0001
	β_1	GLS	−.91178	.29387	−3.103	.0025
SLON	β_2	WLS	1.09292	.21943	4.981	.0001
	β_2	GLS	1.29930	.20927	6.209	.0000
SGOSAND	β_3	WLS	3.37689	1.10466	3.057	.0028
	β_3	GLS	3.03071	.99265	3.053	.0029
SGCTIL	β_4	WLS	3.29626	1.26244	2.611	.0104
	β_4	GLS	2.31200	1.27505	1.813	.0727
LUFD	β_5	WLS	8.11767	1.51401	5.362	.0001
	β_5	GLS	6.67117	1.43211	4.658	.0000
LUFC	β_6	WLS	10.64439	2.57517	4.133	.0001
	β_6	GLS	11.21496	3.00326	3.734	.0003

[1]Variables are defined and discussed on p. 22.
[2]Estimation method: WLS, weighted least-squares estimates; GLS, generalized least-squares estimates.

Table 5. Covariance matrix of the generalized least-squares coefficient estimates for variables used in the recharge equation for the Lower Peninsula of Michigan

Explanatory variable[1]	Intercept	SLAT	SLON	SGOSAND	SGCTIL	LUFD	LUFC
Intercept	0.160280	0.031425	0.035916	-0.120780	-0.135500	-0.314870	-0.110850
SLAT	.031425	.086360	.003867	.113560	−.114580	−.177680	−.526270
SLON	.035916	.003867	.043792	−.063673	−.024737	−.093316	−.013229
SGOSAND	−.120780	.113560	−.063673	.985360	−.117580	−.400730	−.741430
SGCTIL	−.135500	−.114580	−.024737	−.117580	1.62580	.269320	.021116
LUFD	−.314870	−.177680	−.093316	−.400730	.269320	2.05090	−.282580
LUFC	−.110850	−.526270	−.013229	−.741430	.021116	−.282580	9.01960

[1]Variables are defined and discussed on p. 22.

Estimating Normal Basin Recharge Rates

A generalized estimate of normal recharge was computed as

$$\hat{y}_{GLS} = 4.86592 - 0.91178\ \mathrm{SLAT} + 1.29930\ \mathrm{SLON} + 3.03071\ \mathrm{SGOSAND} + 2.31200\ \mathrm{SGCTIL} + 6.67117\ \mathrm{LUFD} + 11.21496\ \mathrm{LUFC}. \quad (15)$$

Basin-specific estimates and the generalized estimate of basin recharge rates were generally within ±4 in/yr of one another; differences were outside this range for only five stations (fig. 16). Four of these five stations were previously identified as influential (1) Manistee River near Grayling, Mich. (USGS gaging station 04123500), (2) Manistee River near Sherman, Mich. (USGS gaging station 04124000), (3) Sturgeon River near Wolverine, Mich. (USGS gaging station 04128000), and (4) Pigeon River near Vanderbilt, Mich. (USGS gaging station 04129000). The fifth station was West Branch Rifle River near Selkirk, Mich. (USGS gaging station 04141500). The generalized estimates of basin recharge are included as appendix A.

The correlation between the estimates, 0.84, indicates that the regression equation accounts for

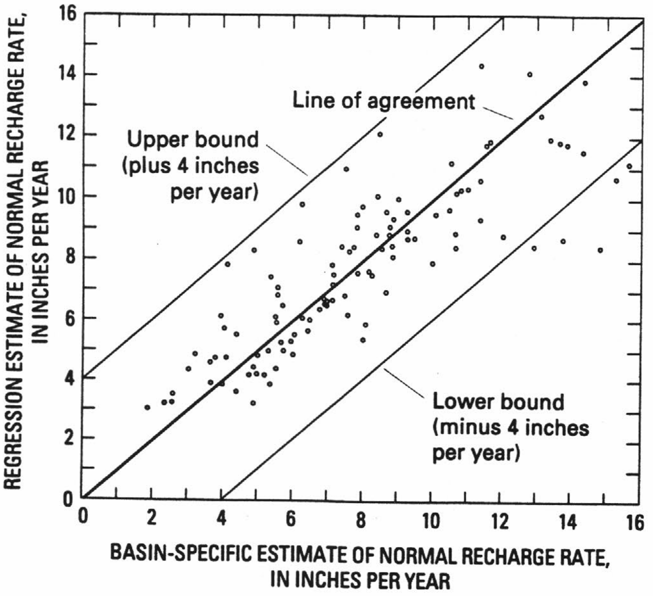


Figure 16. Relation between the basin-specific estimates and the generalized least-squares estimates of normal basin recharge in the Lower Peninsula of Michigan.

about 0.84^2 or 71 percent of the variation in the basin-specific estimates of recharge. Although the GLS estimates of recharge are unbiased, the residuals have a mean of −0.18 in/yr because of the different weights assigned to individual observations by use of equation 4. Thus, the sample GLS estimates of recharge are slightly lower, on the average, than the corresponding basin-specific estimates.

The variance characteristics of the residuals from the GLS regression equation differ among zones (fig. 17). The standard deviation of residuals in Zone B is 2.6 times greater than the average in the other three zones. Four of the five stations with estimates outside the ±4-in. interval are in Zone B; the fifth station is in Zone C and is part of the lower Rifle River Basin. The large absolute values of residuals for these five stations may also partially result from the natural interbasin transfer of water documented in the area by Knutilla and others (1971).

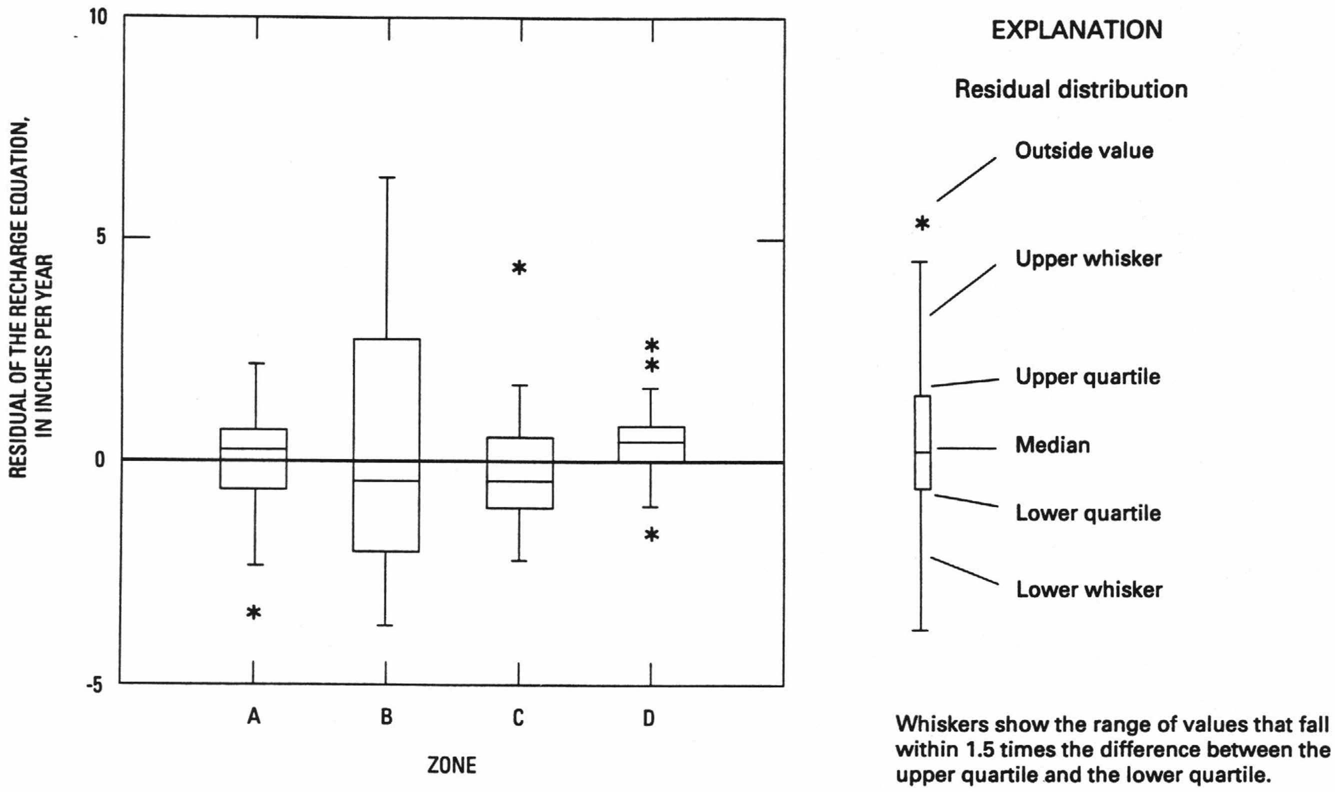


Figure 17. Distribution of residuals from the recharge equation, aggregated by zone in the Lower Peninsula of Michigan. The residuals are computed as the normal basin recharge rate, y_i, minus the recharge rate equation estimate, Y_{GLS}.

Estimating the Spatial Variation of Recharge Rates

The regression equation for estimating recharge (eq. 15) disaggregates the spatial variation in estimated normal annual recharge rates within the Lower Peninsula of Michigan into two primary components. The first component describes a continuous variation in recharge as a function of geographic variables SLAT and SLON and the intercept term. This function describes a plane whose average height near the centroid of basins used in the analysis is 4.86592 in/yr. The surface increases from north to south at a rate of 0.91178 in. per (standardized) degree; recharge increases from east to west at a rate of 1.29930 in. per (standardized) degree.

The second component accounts for discrete changes in recharge rate associated with specific surficial geologic materials and land-use classifications. For a given location, recharge rates tend to be (1) 3.03071 in/yr higher in areas overlain by outwash sand, (2) 2.31200 in/yr higher in areas overlain by coarse-textured till, (3) 6.67117 in/yr higher in areas classified as deciduous forests, and (4) 11.21496 in/yr higher in areas classified as coniferous forest than in areas of other surficial materials or land-use classifications. All effects are additive, so that an area of outwash sand and deciduous forest has a discrete component of recharge of 9.7019 in/yr. Discrete effects are added to continuous effects to estimate recharge.

A generalized estimate of recharge rates was computed across an imaginary grid overlying the Lower Peninsula by use of equation 15 (fig. 18). Each square cell in the grid had an area of 0.3861 mi^2 (1 square kilometer). Only one type of the surficial geologic material and one land-use classification was identified per cell. Although grid cells were smaller than any of the basins used in the analysis, no bias or systematic change in variance is apparent with respect to basin size (fig. 19).

The results indicate that recharge rates are generally greatest in the northwestern part of the Lower Peninsula in areas where glacial outwash sand and coniferous forests commonly coincide. Recharge is generally least in the east-central part of the Lower Peninsula. Total land areas within the Lower Peninsula associated with various recharge rates can be determined by use of figure 20.

Finally, a measure of the relative uncertainty in the spatial estimate of recharge is provided by a map of estimated standard error (fig. 21). The map was obtained by computing the standard error for each grid element by use of equation 14. The standard error can be used to construct an interval about the estimate that is likely to contain the true value. Commonly, an interval of plus or minus twice the standard error is used to approximate an interval that has about 95-percent probability of containing the true value. However, because of the large number of intervals computed and the spatial correlation among estimates, a strict interpretation of these intervals for hypothesis testing is not appropriate. Rather, the map is intended as a relative indication of the uncertainty in the recharge estimate. The results indicate that the greatest uncertainties of the recharge estimates are in areas associated with both the coniferous forest land-use classification and the outwash sand glacial deposits. The lowest variability of the recharge estimate is in the central and eastern part of the Lower Peninsula.

SUMMARY AND CONCLUSIONS

This report describes the development of an estimate of the spatial variation of natural ground-water-recharge rates in the Lower Peninsula of Michigan. The estimated recharge rates approximate the average recharge rates during the period 1951–80. In this report, natural recharge refers to recharge that results directly from infiltration of precipitation or from runoff and subsequent infiltration from surface-water bodies. Artificial recharge or recharge from irrigation is not included.

The recharge estimates were developed through the analysis of 3,456 station-years of daily streamflow data from 114 selected USGS streamflow-gaging stations. Gaging stations were selected where streamflow and record characteristics were thought to be appropriate for reliable estimation of recharge characteristics from the analysis of daily streamflow records. Basins were not selected where streamflow was known to be significantly affected by regulation, diversion, flow augmentation, hydraulic control structures, or other anomalies. A minimum of 10 yr of continuous streamflow data was required.

The annual ground-water components of streamflow were determined by use of a hydrograph-separation technique referred to as "streamflow partitioning." This technique provides an estimate of recharge that is similar to estimates obtained by other widely used techniques for estimating recharge by use of hydrograph-separation techniques. Not included,

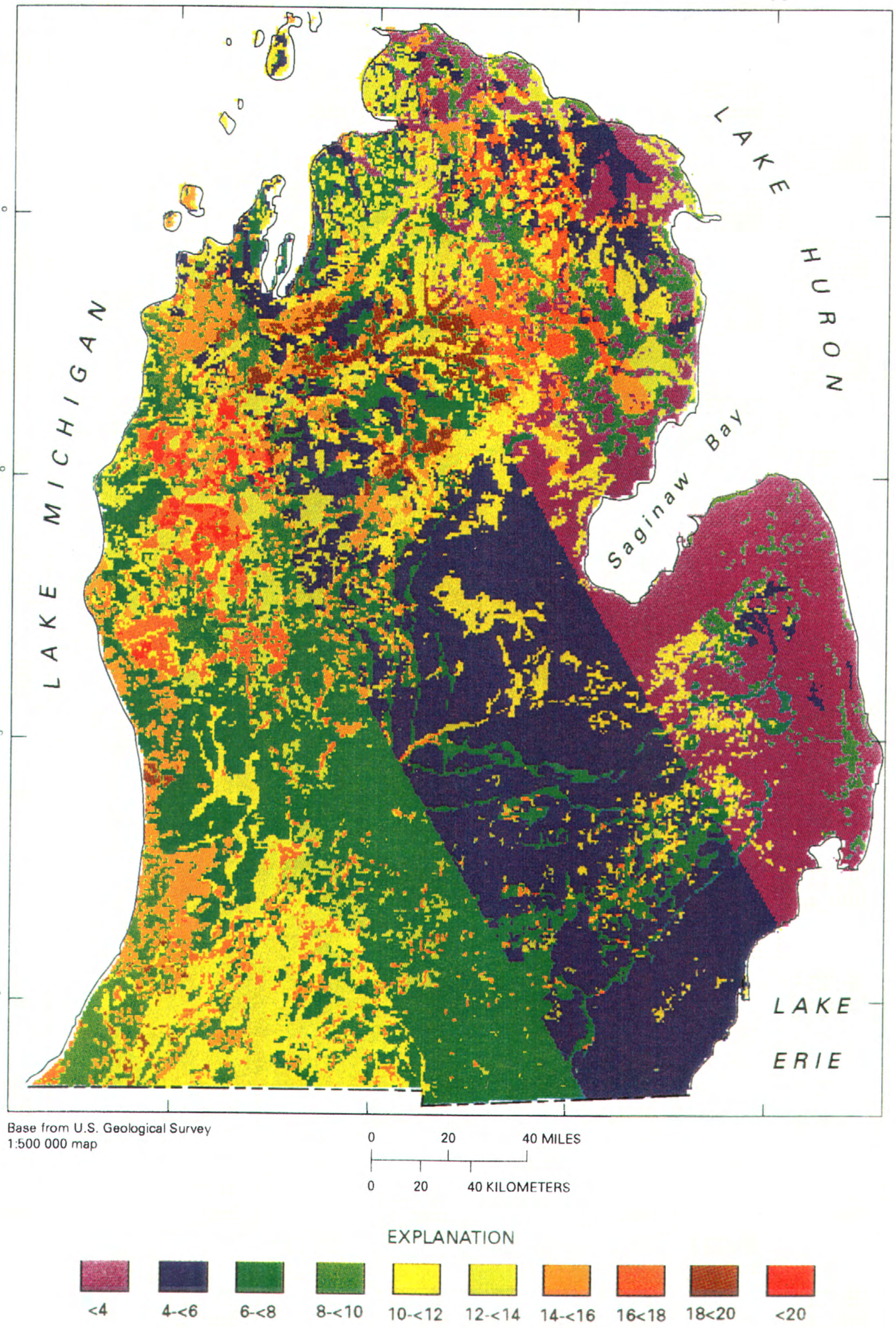


Figure 18. Spatial variation of the generalized estimate of ground-water-recharge rates, Lower Peninsula of Michigan.

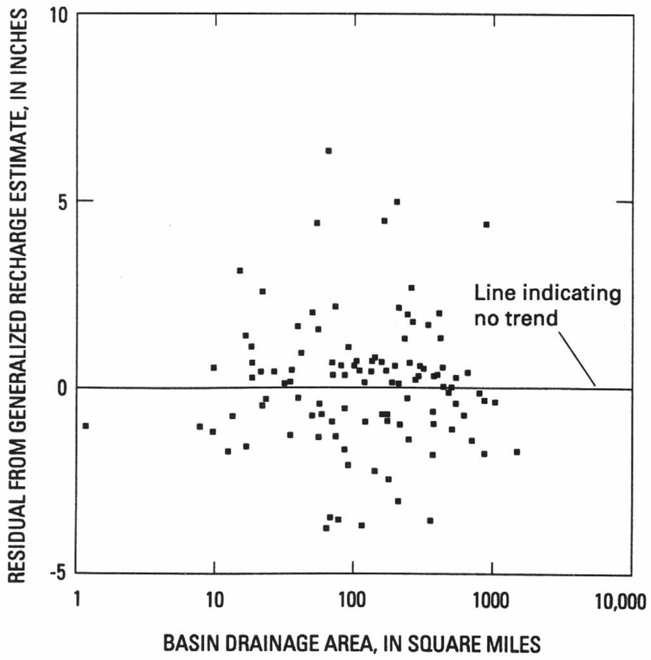


Figure 19. Distribution of the residuals from the recharge rate equation (eq. 15) with basin area, Lower Peninsula of Michigan. The residuals are computed as the normal basin recharge rate, y_i, minus the recharge rate equation estimate, Y_{GLS}.

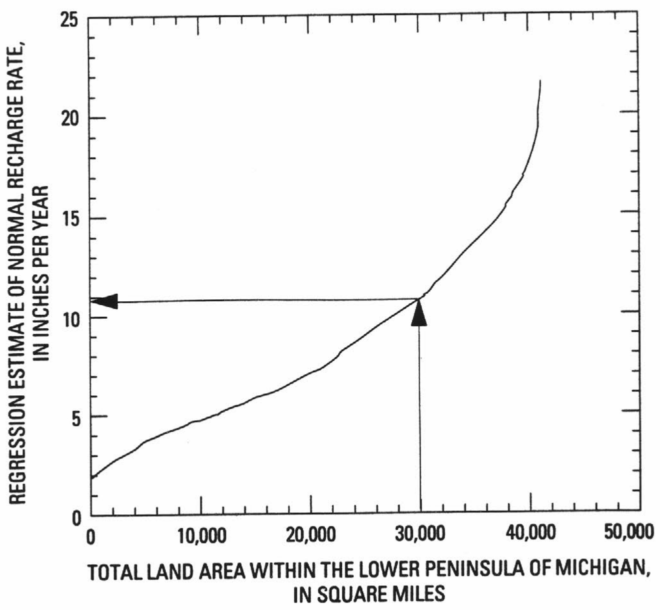


Figure 20. Relation between land area and estimated normal ground-water-recharge rates, Lower Peninsula of Michigan. For example, 30,000 mi^2 in the Lower Peninsula of Michigan are estimated to have a normal recharge rate of 10.9 in/yr or less.

however, are (1) recharge that does not emerge as streamflow but leaves the basin as ground water, and (2) recharge that is lost to evapotranspiration in the riparian zone.

Annual ground-water discharge ranged from 0.19 in/yr to 22.7 in/yr. The average ground-water discharge was 8.41 in/yr. The average annual percentage of streamflow identified as ground-water discharge ranged among basins from 29.6 to 97.0 percent.

The annual ground-water-discharge components were used to compute basin-specific estimates of normal recharge rate. The normal recharge rates remove the temporal variation in average recharge associated with different time periods of data collection. A set of basin-specific equations was developed by use of multiple-regression analysis. Explanatory variables generally included annual precipitation and the previous year's ground-water-discharge component. The steady-state solution of these equations at the normal precipitation rate for the period 1951–80 was used to compute basin-specific estimates of recharge.

The basin-specific estimates of normal recharge were related to basin characteristics to develop a generalized estimate of recharge. The generalized estimate describes the spatial variation of recharge within gaged basins and across ungaged areas. A recharge equation was developed to compute the generalized estimate. The recharge equation was identified by selecting explanatory variables that were physically meaningful and that explained a large part of the variability in the basin-specific estimates of recharge. Initial coefficient estimates were computed by use of weighted least squares; final estimates were computed by use of generalized least squares. Four of the 114 selected stations were removed from the analysis because of concerns about possible discrepancies between ground-water divides and surface-water divides.

The regression equation for estimating recharge (eq. 15) disaggregates the spatial variation in recharge into a continuous component and a discrete component. The continuous component, which is thought to be associated with climatic factors, is approximated by a plane surface that rises from north to south and from east to west across the Lower Peninsula. The rate of change in recharge with position is described by coefficients associated with standardized values of latitude and longitude. The average height of the surface is described by an intercept term in the equation. The discrete component, which is thought to be associated with the infiltration capacities of soils, is a function of specific surficial geologic materials and land-use clas-

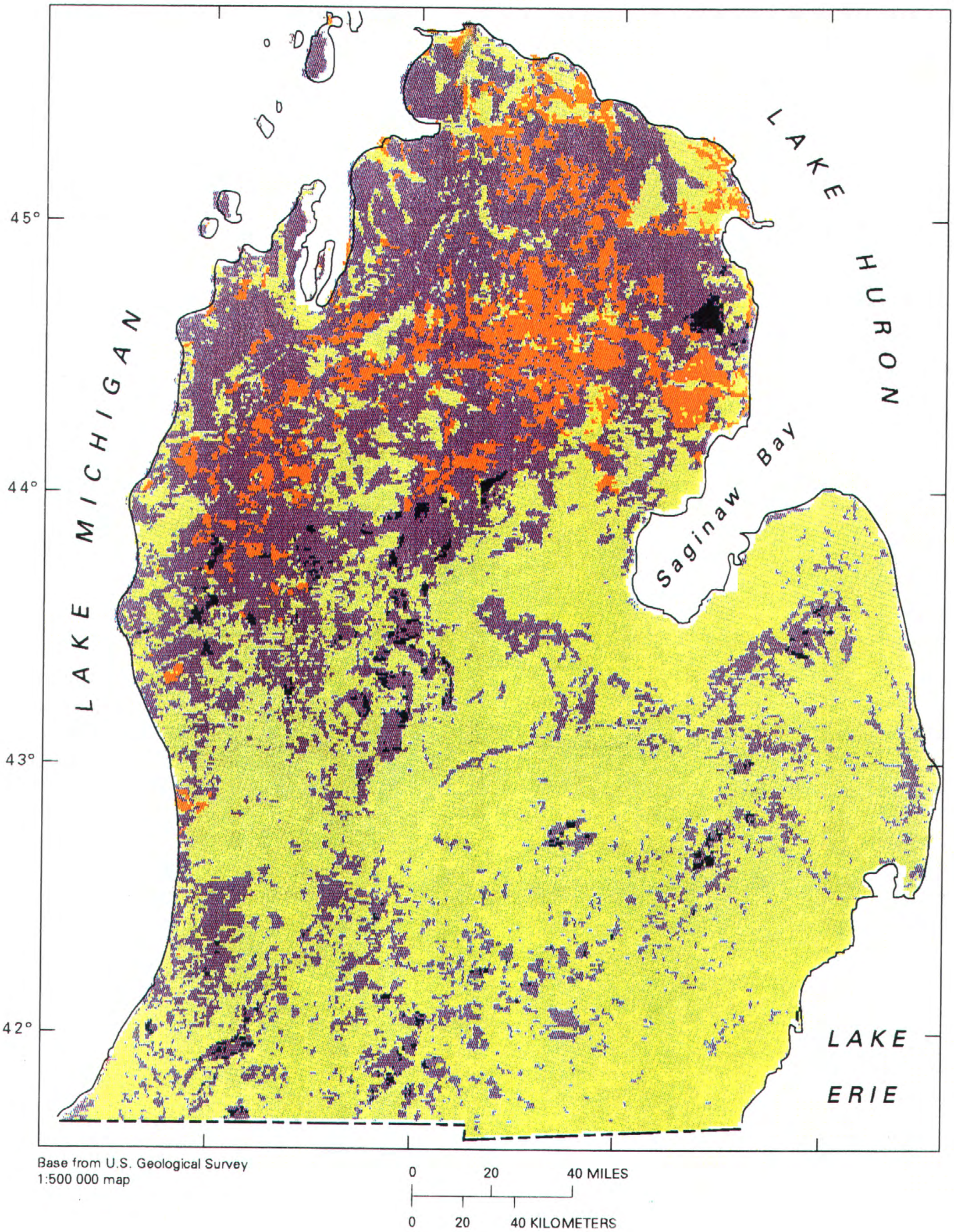
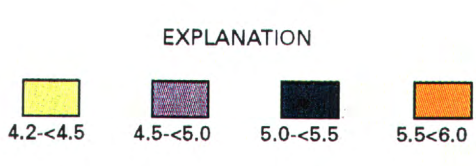


Figure 21. Relative uncertainty of estimated recharge rates, Lower Peninsula of Michigan.



sifications. Results of analysis indicate that recharge is generally greater in areas overlain by outwash sand, in areas overlain by coarse-textured till, and in areas classified as deciduous or coniferous forests than in areas of other surficial geologic materials or land-use classifications.

The accuracy of the recharge estimates is spatially variable. The relative uncertainty is higher than average in the northwestern part of the Lower Peninsula. Some of this error is thought to be caused by inconsistencies between surface-water and ground-water divides. The uncertainties also vary with recharge estimates. Relative uncertainties tend to be greatest in areas overlain by outwash sand and coniferous forests and least in the central and eastern part of the Lower Peninsula where outwash sand, coarse-textured till, and forests are uncommon.

The generalized estimate is computed on the basis of a statistical relation between the main effects of ground-water recharge and basin characteristics. Higher order effects, interactions among main effects, and effects of human activity could not be determined from available data. Estimates based on alternative techniques that properly account for these and other effects may supersede the generalized estimate for estimating local recharge rates.

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APPENDIX A. GENERALIZED RECHARGE AND EXPLANATORY VARIABLES AT SELECTED STATIONS

[**SLAT** and **SLON** are the standardized latitude and longitude, respectively; **SGOSAND** and **SGCTIL** are the proportions of surficial geologic materials composed of outwash sand and coarse-textured till, respectively; and **LUFD** and **LUFC** are the proportions of land use associated with deciduous forest and coniferous forest, respectively]

USGS gaging station number	Generalized estimate of normal basin recharge (inches per year)	Value of the explanatory variable used in the regression analysis					
		SLAT	SLON	SGOSAND	SGCTIL	LUFD	LUFC
04096400	8.423	−1.29842	0.52250	0.41941	0.09341	0.03114	0.00000
04096515	7.909	−1.43313	.55956	.22400	.12000	.00800	.00000
04096600	9.489	−1.40170	.70145	.47067	.23748	.06867	.00000
04096900	10.262	−1.14349	.91217	.53444	.12827	.18765	.00000
04097170	10.626	−1.09185	1.24784	.63057	.00000	.18471	.00000
04097540	10.160	−1.51172	1.05936	.72961	.04292	.03433	.00000
04098500	10.329	−1.59592	1.00959	.73529	.11765	.02941	.00000
04101800	11.833	−1.27933	1.89165	.47153	.23796	.20438	.00000
04102500	11.765	−1.07052	1.85670	.40918	.07170	.31549	.00000
04102700	12.721	−.93019	1.91706	.14672	.02317	.60232	.00000
04105000	8.715	−.80670	.73216	.20219	.00000	.23224	.00000
04105500	9.070	−.98969	.64109	.35294	.06353	.18776	.00000
04105700	11.754	−.84487	1.16419	.74138	.00000	.35345	.00000
04106000	9.567	−.96612	.73533	.42988	.04907	.21714	.00000
04108600	9.067	−.53503	1.46068	.46073	.00000	.06283	.00000
04108800	8.301	−.44858	1.85247	.16931	.00000	.01587	.00000
04109000	8.566	−1.09634	.07988	.62585	.16553	.04762	.00000
04110000	7.812	−.80446	−.01224	.33333	.20635	.11111	.00000
04111500	7.064	−.66862	.08411	.21951	.00000	.12195	.00000
04112000	5.517	−.58218	.09259	.00000	.00000	.00000	.00000
04112500	6.101	−.58891	−.05566	.10364	.00000	.06836	.00000
04114500	6.620	−.39245	.14235	.09574	.17952	.07580	.00000
04115000	6.120	−.09720	.23871	.14950	.00820	.05743	.00000
04116500	8.941	.11161	1.03924	.21174	.28900	.22734	.00000
04117000	9.963	−.71128	.90370	.20000	.00000	.40000	.00000
04117500	8.458	−.63606	.80840	.22243	.01776	.18692	.00000
04118000	8.826	−.57207	.94711	.21564	.00900	.22986	.00000
04118500	9.337	.06670	1.47233	.26861	.03942	.25693	.00000

APPENDIX A. GENERALIZED RECHARGE AND EXPLANATORY VARIABLES AT SELECTED STATIONS—Continued

USGS gaging station number	Generalized estimate of normal basin recharge (inches per year)	Value of the explanatory variable used in the regression analysis					
		SLAT	SLON	SGOSAND	SGCTIL	LUFD	LUFC
04121000	9.742	1.36896	.55850	.67452	.04711	.31370	.10278
04121300	9.769	1.23537	1.14830	0.44817	0.00000	0.38278	0.05582
04121500	10.055	1.17474	.83487	.47870	.09742	.34247	.10828
04121900	9.623	.48432	1.08265	.44531	.10938	.32813	.00000
04122100	8.831	.17897	2.05048	.00000	.00000	.21951	.00000
04122200	11.950	.47310	1.83658	.41812	.11894	.52699	.00640
04122500	14.111	.75712	1.76882	.51571	.09195	.64566	.13856
04123000	13.830	1.03105	1.93083	.64286	.00000	.60248	.12733
04123500	10.706	1.89884	.65380	.56560	.00000	.48105	.16035
04124000	11.166	1.63053	1.00006	.51429	.07560	.34462	.21890
04124500	7.811	1.04901	1.23619	.01220	.23780	.25610	.00000
04125000	9.548	1.09391	1.29655	.27193	.11696	.30702	.07602
04125500	11.555	1.08381	1.36749	.36593	.08296	.33333	.21185
04126200	14.368	1.04452	1.71164	.76035	.00000	.44805	.26190
04128000	8.712	2.27156	.47591	.24663	.27746	.46628	.07129
04129000	8.432	2.14470	.31707	.29310	.35632	.31609	.11494
04129500	11.152	2.25472	.29695	.28906	.50000	.28385	.35938
04131500	7.405	2.38719	−.10119	.03846	.96154	.23932	.08120
04132500	11.856	2.00774	−.09907	.24103	.56239	.49402	.32308
04134000	6.693	2.29064	−.34474	.17355	.62603	.09091	.15909
04135500	12.095	1.86292	.54473	.47308	.00000	.66154	.21154
04135600	10.959	1.81465	.45367	.36313	.00000	.33520	.34078
04138000	9.344	1.34202	−.47286	.10288	.00000	.39506	.30041
04138500	6.498	1.24996	−.35639	.00737	.00000	.48157	.00000
04140000	8.806	1.35212	−.08531	.07143	.00000	.33929	.25000
04141000	3.541	1.27690	−.12343	.00000	.00000	.00000	.00000
04141500	8.489	1.26905	.00787	.02890	.00000	.41040	.17341
04142000	8.888	1.26006	−.11496	.08601	.00000	.39220	.21789
04143500	4.209	.69201	−.11390	.00000	.00000	.01832	.00000
04144000	6.516	−.50696	−.46969	.16092	.08150	.16823	.00000

APPENDIX A. GENERALIZED RECHARGE AND EXPLANATORY VARIABLES AT SELECTED STATIONS—Continued

USGS gaging station number	Generalized estimate of normal basin recharge (inches per year)	Value of the explanatory variable used in the regression analysis					
		SLAT	SLON	SGOSAND	SGCTIL	LUFD	LUFC
04145000	6.023	–.33295	–.32038	.15245	.04719	.10466	.00000
04146000	5.929	–.22630	–.93031	.16296	.08148	.20741	.00000
04146063	6.195	–.18252	–1.02031	0 .13345	0 .03378	0.30068	0.00000
04147990	5.506	.02517	–.73865	.03922	.00000	.22549	.00000
04148200	9.463	–.38123	–.72064	.36364	.45455	.45455	.00000
04148300	6.058	–.31387	–.58299	.14331	.04459	.16879	.00000
04148440	6.817	–.32622	–.74924	.12000	.11333	.30000	.00000
04148720	4.428	–.04444	–.53640	.00000	.00000	.03279	.00000
04150000	4.355	.28674	–1.32527	.18770	.06782	.11199	.00000
04150500	4.741	.36308	–1.31574	.16042	.08333	.18542	.00000
04151500	5.731	.29572	–1.09020	.13866	.06474	.29706	.00000
04152500	8.422	.89072	.49285	.16446	.07604	.45181	.00354
04153500	6.107	.61567	.46214	.02314	.00000	.16967	.00000
04154000	8.694	.61680	.79675	.30208	.10701	.32860	.00000
04154500	8.284	.55056	.65698	.22052	.07462	.33355	.00000
04157500	3.213	.51464	–.91125	.00000	.00000	.00000	.00000
04158000	3.061	.57189	–.98749	.00000	.00000	.00000	.00000
04158500	3.266	.62465	–1.16962	.00000	.00000	.07333	.00000
04159500	3.272	.21714	–1.53388	.03739	.02546	.06364	.00000
04159900	4.749	–.06689	–1.32210	.18925	.00000	.14486	.00000
04160000	4.595	–.06240	–1.41210	.17457	.00000	.14655	.00000
04160570	4.994	–.13537	–1.23844	.00000	.00000	.24194	.00000
04160600	3.630	–.20048	–1.35810	.00000	.00000	.05189	.00000
04160800	6.500	–.46430	–1.00972	.54839	.00000	.12903	.00000
04160900	6.812	–.46767	–.93772	.58454	.00000	.14493	.00000
04161100	4.976	–.52268	–1.06902	.29412	.00000	.01961	.00000
04161500	6.926	–.38123	–1.00549	.57282	.10680	.15534	.00000
04161540	5.870	–.42501	–1.05949	.34359	.05641	.12308	.00000
04161580	6.653	–.36775	–1.18232	.18841	.00000	.36232	.00000
04161800	6.362	–.40592	–1.14103	.26891	.00000	.26891	.00000

APPENDIX A. GENERALIZED RECHARGE AND EXPLANATORY VARIABLES AT SELECTED STATIONS—Continued

USGS gaging station number	Generalized estimate of normal basin recharge (inches per year)	Value of the explanatory variable used in the regression analysis					
		SLAT	SLON	SGOSAND	SGCTIL	LUFD	LUFC
04163400	3.872	−.61137	−1.19397	.00000	.00000	.00000	.00000
04163500	3.913	−.61024	−1.23633	.00000	.00000	.01449	.00000
04164100	5.384	−.33632	−1.23739	.23881	.00000	.16418	.00000
04164300	3.259	−.28805	−1.43858	0.00000	0.00000	0.00000	0.00000
04164500	3.852	−.38347	−1.38034	.06225	.00000	.03614	.00000
04164800	4.183	−.47890	−1.31680	.00847	.00000	.08475	.00000
04166000	4.812	−.63045	−1.07537	.21296	.00000	.01852	.00000
04166100	4.377	−.69107	−.99702	.04032	.00000	.00806	.00000
04166200	4.166	−.75394	−1.06796	.00000	.00000	.00000	.00000
04166300	4.865	−.73598	−.88689	.07547	.00000	.03774	.00000
04167000	5.286	−.85385	−.80324	.11511	.00000	.05036	.00000
04168000	4.852	−.97173	−.83077	.00909	.00000	.02273	.00000
04169500	8.391	−.56422	−.82548	.59494	.00000	.34177	.00000
04170000	7.488	−.61698	−.79900	.50959	.00000	.23288	.00000
04171500	8.371	−.65964	−.51946	.40659	.00000	.35165	.00000
04172000	7.602	−.67311	−.69947	.53715	.00244	.20950	.00000
04173000	7.500	−.72924	−.52475	.47437	.02671	.17256	.00000
04173500	5.640	−1.00766	−.29709	.03056	.00000	.02222	.00000
04175340	5.259	−1.13002	−.67829	.00000	.00000	.03665	.00000
04175600	8.095	−1.19289	−.00801	.43052	.19346	.05995	.00000
04175700	7.576	−1.22320	−.11813	.37414	.09491	.05915	.00000
04176000	7.172	−1.27821	−.10225	.28618	.05854	.04065	.00000