Indirect Ground-Water Discharge to the Great Lakes

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Indirect Ground-Water Discharge to the Great Lakes

By D.J. Holtschlag and J.R. Nicholas

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	Length	
inch (in.)	25.4	millimeter
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square mile (mi^2)	2.59	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

Estimates of the average ground-water component of streamflow for 195 streams in the United States part of the Great Lakes Basin range from 25 to 97 percent. Among the selected streams, the average ground-water component of streamflow was 67.3 percent. Estimates of the ground-water component of streamflow are based on hydrograph separation of 5,735 years of daily streamflow data. Incorporation of these estimates into the basin water supply for the Great Lakes shows that indirect discharge of ground water to the Great Lakes ranges from 22 percent of the basin water supply of Lake Erie to 42 percent of the basin water supply for Lake Ontario.

INTRODUCTION

Historically, scientists and water-resource managers have viewed ground water that flows directly from aquifers to the Great Lakes as a small fraction of the basin water supply. This perspective, however, does not account for the substantial amount of ground-water that flows indirectly into the Great Lakes as a component of streamflow.

In estimates of basin water supply for the Great Lakes, direct ground-water discharge generally is assumed to be small, typically within the uncertainty limits associated with estimates of precipitation, surface runoff, diversions, and evaporation. Recent work by Grannemann and Weaver (in press) summarizes studies of direct ground-water discharge to the Great Lakes and generally corroborates this assumption. They indicate that, while little is known about direct ground-water discharge to the Great Lakes, available information suggests that such direct discharge to the lakes is small. For Lake Michigan, the only Great Lake for which sufficient information is available to make a lake-wide estimate, direct ground-water discharge is only about 5 percent of the basin water supply for the lake. Direct ground-water discharge is difficult to estimate because it is determined by geologic and hydraulic properties that are difficult to measure locally and are highly variable from place to place.

Indirect ground-water discharge has not been explicitly considered in estimates of basin water supply for the Great Lakes. Instead, it has been incorporated into the streamflow component of basin water supply. Streamflow includes a surface-runoff component and a ground-water component. The surface-runoff component results from precipitation that flows overland to a stream or otherwise flows to a stream without percolating into an aquifer. The ground-water component results from that part of precipitation that infiltrates into the soil, percolates into an aquifer, and then flows to a stream. The ground-water component of streamflow in the Great Lakes Basin constitutes indirect ground-water discharge to the Great Lakes. Indirect ground-water discharge can be readily estimated from streamflow records that are available from gaging stations throughout the Great Lakes Basin.

In June 1998, the U.S. Geological Survey (USGS), in cooperation with the Great Lakes Protection Fund, began a study to summarize available data and information needs regarding the ground-water component of the Great Lakes basin water supply. This report presents estimates of indirect ground-water discharge made by applying hydrograph separation techniques to historical data from selected USGS streamgaging stations and relates these estimates to the Great Lakes basin water supply.

The authors gratefully acknowledge the assistance of Nancy Baker, the Geographic Information Specialist for the USGS in Indiana, in the preparation of the illustrations. We also thank hydrologists at NOAA’s Great Lakes Environmental Research Laboratory in Ann Arbor, Michigan, for assistance in retrieving and understanding basin water supply information for the Great Lakes.

INDIRECT GROUND-WATER DISCHARGE TO THE GREAT LAKES

The USGS has measured streamflow at 770 gaging stations in the Great Lakes Basin, some beginning as early as 1900. About 300 of these stations currently are active. Data from USGS gaging stations provide a record of daily streamflow for flood forecasting, hydroelectric power generation, water-quality management, and regional streamflow information. In this report, an analysis of streamflow hydrographs is used to provide regional information on the indirect ground-water component of flow to the Great Lakes.

Ground-Water Component of Streamflow at Selected Gaging Stations

Hydrograph separation provides a systematic method for identifying the ground-water and surface-runoff components of streamflow. The hydrograph separation method used in this report is based on a technique referred to as “streamflow partitioning” (Rutledge, 1993). This technique, implemented in the computer program PART (Rutledge, in press), scans the streamflow record for days that fit a requirement of antecedent recession (based on drainage area), designates ground-water flow to be equal to streamflow on these days, and then linearly interpolates the daily record of ground-water flow for days that do not fit the requirement of antecedent recession. The technique was selected because it was developed specifically to estimate the ground-water component of streamflow in the northeastern part of the United States, it produces estimates that are in close agreement with other manual and automated techniques, and it has data requirements that are consistent with available USGS data.

In this report, 5,735 years of daily streamflow values from 195 streamgaging stations, an average of 29.4 years per station, were analyzed to estimate indirect ground-water discharge to the Great Lakes. To provide appropriate estimates of indirect ground-water discharge, only those stations that satisfied the following criteria were selected: four or more years of continuous streamflow record were available, records were not significantly affected by streamflow regulation or diversion, and the stream drained an area smaller than 500 square miles.

Estimates of the average ground-water component of flow for the 195 streams range from 25 to 97 percent of the streamflow (fig. 1 and table 1). Among the selected gaging stations, the average ground-water component of streamflow was 67.3 percent. In general, the highest percentages of ground-water discharge are associated with basins having the highest percentages of land area covered by coarse-textured soils and undisturbed vegetation. Lowest percentages of ground-water discharge are associated with basins having the highest percentage of impervious areas or basins having the highest percentage of thin, tight soils overlying less permeable geologic materials. Like streamflow, the ground-water component of streamflow varies seasonally, generally reaching a maximum in March or April and a minimum in August or February (fig. 2).

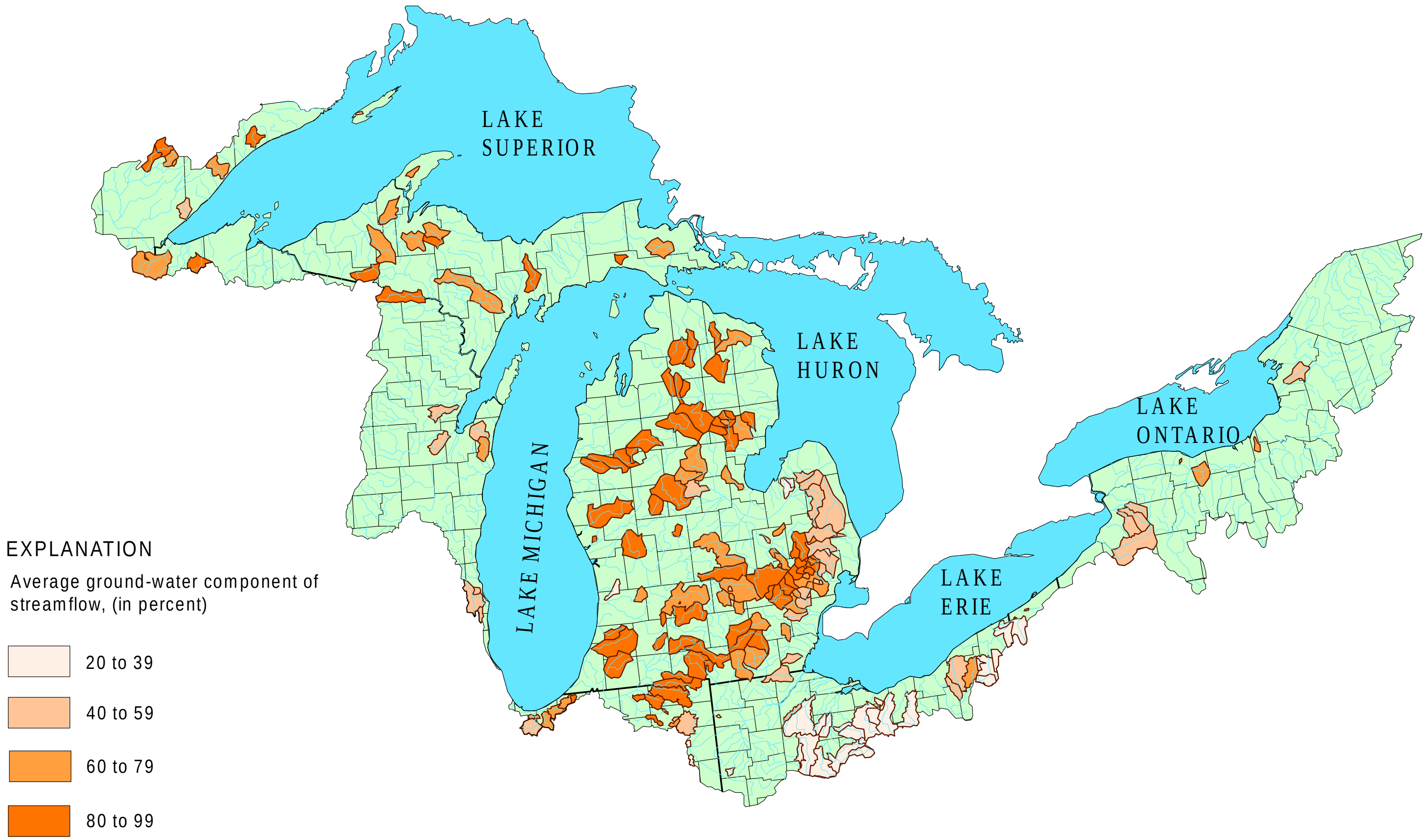

Figure 1. Average ground-water component of streamflow for selected streams in the Great Lakes.

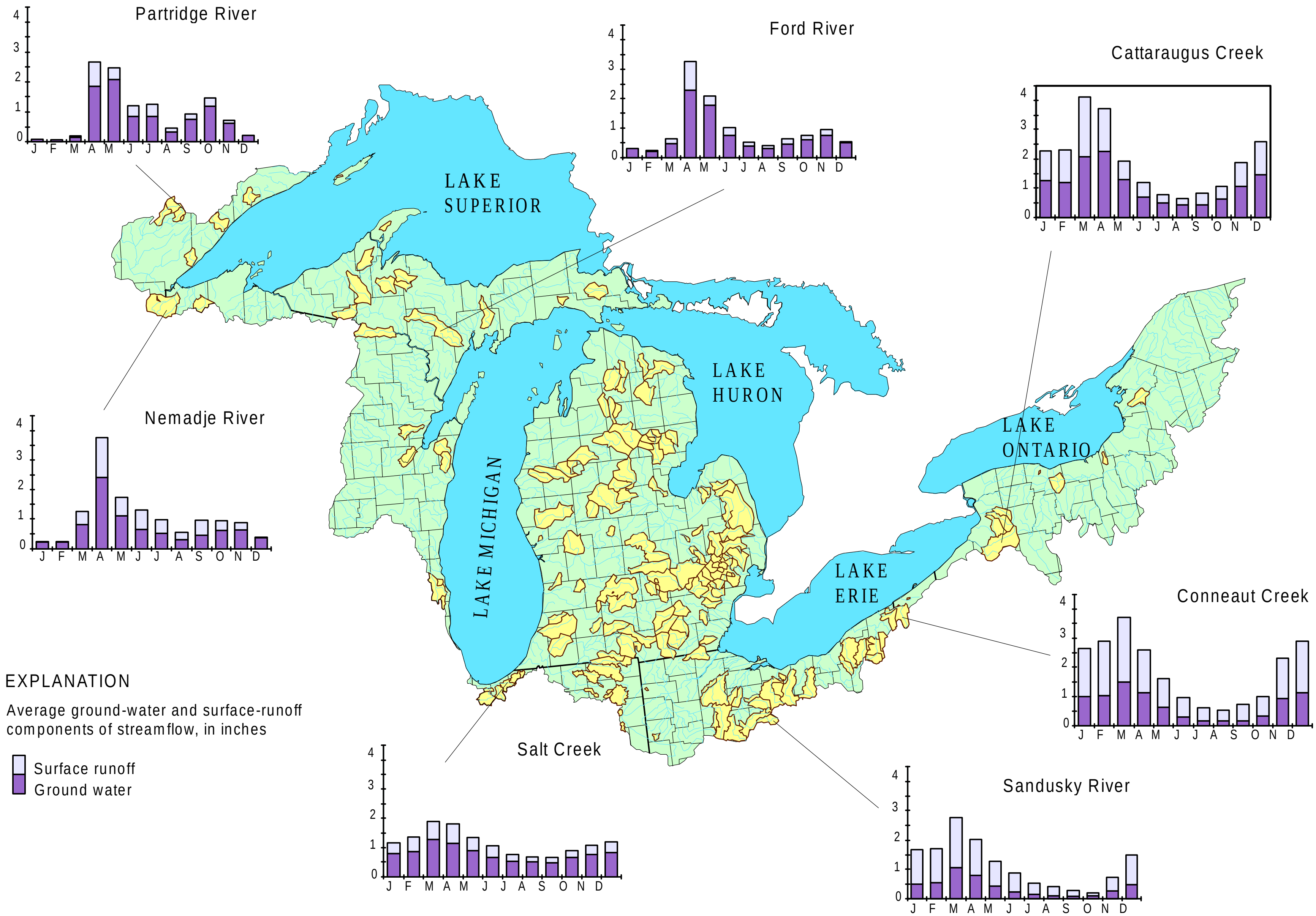

Figure 2. Seasonal variability of the average ground-water and surface-runoff components of streamflow for seven streams in the Great Lakes Basin..

Table 2. Basin water supply for the Great Lakes.

Lake	Overlake precipitation (percent)	Surface-runoff (percent)	Indirect ground-water discharge (percent)
Superior	56.3	11.0	32.7
Michigan	56.2	9.3	34.5
Huron	42.2	16.3	41.5
Erie	53.5	24.3	22.2
Ontario	34.8	22.8	42.4

Ground-Water Component of Streamflow Discharging to the Great Lakes

The drainage areas of the 195 gaging stations selected for hydrograph separation analysis represent only 13.6 percent of the total drainage area of the Great Lakes Basin. Thus, a large percentage of the Great Lakes Basin is not monitored by the selected gaging stations. These preliminary estimates of the total contribution of indirect ground-water to the basin water supply of the Great Lakes, therefore, could be improved by similar analysis of streamflow data available for Canadian streams and by quantitatively relating indirect ground-water discharge to selected physical characteristics of the entire Great Lakes Basin, such as was done by Holtschlag (1997) for Michigan’s Lower Peninsula.

In this report, it is assumed that the average ground-water component of streamflow in a particular lake basin is equal to the average ground-water component of streamflow estimated from the gaged streams in that basin. Thus, the average ground-water component of streamflow for the Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario Basins were computed on the basis of data from 15, 64, 56, 56, and 4 gaging stations, respectively. Using this approach, the average ground-water component of streamflow ranges from 48 percent for Lake Erie to 79 percent for Lake Michigan (fig. 3).

Indirect Ground-Water Discharge as a Component of Basin Water Supply

Croley and Hunter (1994) have compiled data on the total streamflow and overlake precipitation to describe the basin water supply for each Great Lake. The percentage ground-water component of streamflow for each Great Lake provides the basis for subdividing the total streamflow into indirect ground-water and surface-runoff components. This subdivision, generally based on data from 1950 to 1990, provides information on the ground-water component of the basin water supply that was not previously available. Results of these calculations (appendix 1) indicate that indirect ground-water discharge ranges from the smallest component of basin water supply for Lake Erie (22 percent) to the largest component of basin water supply for Lake Ontario (42 percent) (table 2 and fig. 4).

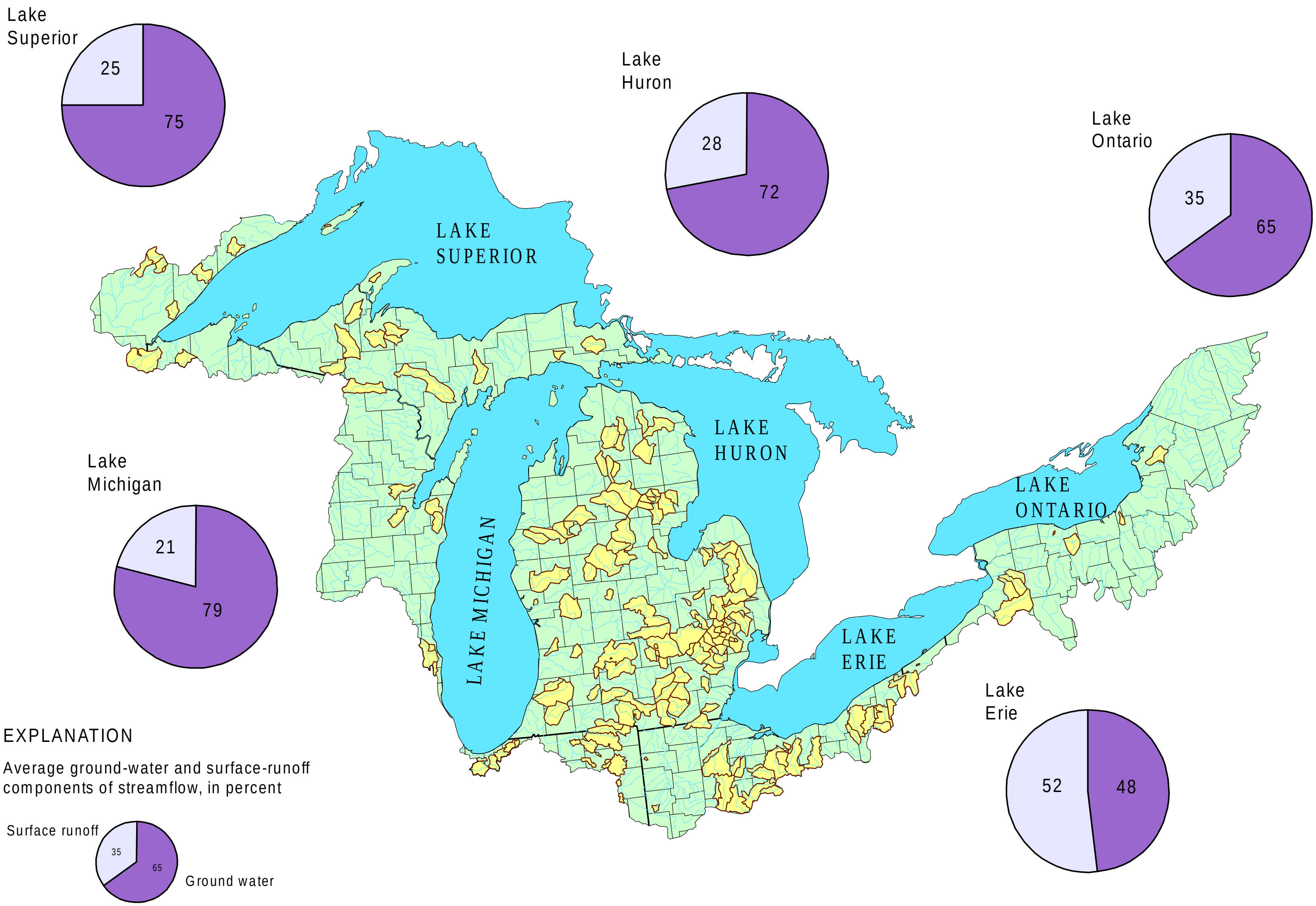

Figure 3. Average ground-water and surface-runoff components of streamflow for the Great Lakes.

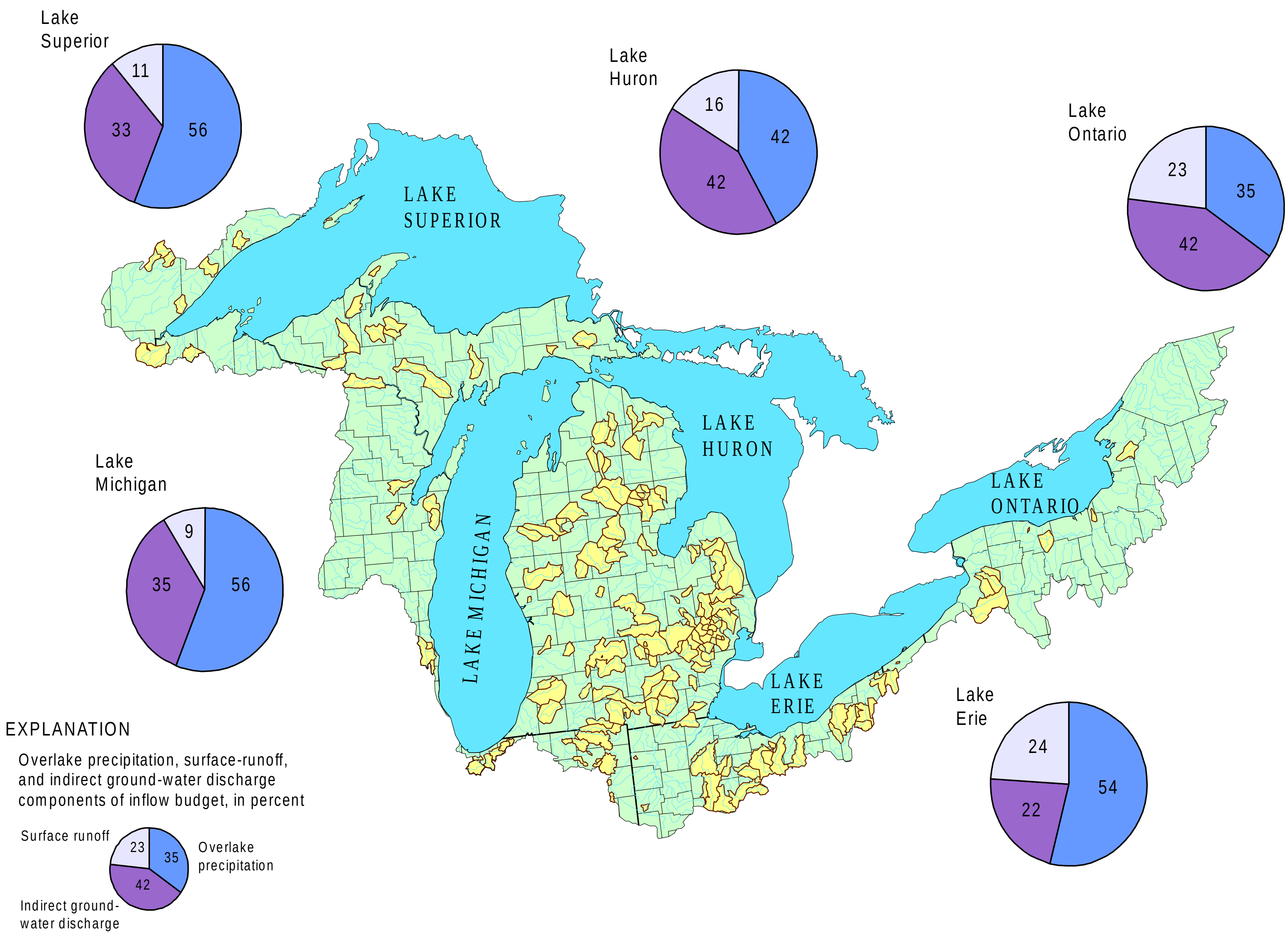

Figure 4. Basin water supply for the Great Lakes.

CONCLUSIONS

Based on hydrograph separation analysis of streamflow data from 195 USGS gaging stations in the Great Lakes Basin, the average ground-water component of streamflow is 67.3 percent. This ground-water component of streamflow constitutes the indirect ground-water discharge to the Great Lakes, which ranges from 22 percent (Lake Erie) to 42 percent (Lake Ontario) of the basin water supply for the Great Lakes. Thus, even without explicitly accounting for direct ground-water discharge, ground water is a large component of the basin water supply of the Great Lakes.

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Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
	STATIONS GAGING STREAMS TRIBUTARY TO LAKE SUPERIOR					
04001000	Washington Creek at Windigo, MI	13.2	33	16.4	12.4	75.6
04012500	Poplar River at Lutsen, MN	112	21	106	89.5	84.8
04014500	Baptism River near Beaver Bay, MN	140	59	169	110	65.3
04015330	Knife River near Two Harbors, MN	85.6	22	93.0	48.9	52.6
04015475	Partridge River above Colby Lake at Hoyt Lakes, MN	106	9	91.4	70.4	77.0
04017000	Embarrass River at Embarrass, MN	88.3	22	64.5	51.9	80.5
04018000	Embarrass River near McKinley, MN	171	8	109	93.1	85.6
04024098	Deer Creek near Holyoke, MN	7.8	19	7.45	4.02	53.9
04024430	Nemadji River near South Superior, WI	420	24	408	257	62.9
04025500	Bois Brule River at Brule, WI	118	52	172	163	94.6
04033000	Middle Branch Ontonagon River near Paulding, MI	164	52	170	152	89.5
04035000	East Branch Ontonagon River near Mass, MI	272	36	257	194	75.6
04040500	Sturgeon River near Sidnaw, MI	171	53	213	161	75.5
04042500	Otter River near Elo, MI	162	29	215	161	75.1
04043050	Trap Rock River near Lake Linden, MI	28	31	45.2	33.6	74.3

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
	STATIONS GAGING STREAMS TRIBUTARY TO LAKE MICHIGAN					
04046000	Black River near Garnet, MI	28	26	29.1	25.4	87.3
04057510	Sturgeon River near Nahma Junction, MI	183	31	196	170	86.9
04059500	Ford River near Hyde, MI	450	43	378	294	77.8
04060993	Brule River near Florence, MI	366	52	353	312	88.3
04062200	Peshekee River near Champion, MI	133	16	210	158	75.3
04062230	Michigamme River near Michigamme, MI	194	13	283	252	89.1
04071858	Pensaukee River near Pensaukee, WI	134	23	89.7	50.0	55.8
04072150	Duck Creek near Howard, WI	108	9	56.6	25.0	44.1
04085200	Kewaunee River near Dewaunee, WI	127	29	88.4	49.1	55.5
04085281	East Twin River at Mishicot, WI	110	23	78.6	50.8	64.6
04087204	Oak Creek at South Milwaukee, WI	25	34	23.1	9.92	43.0
04087240	Root River at Racine, WI	190	34	151	79.7	52.8
04087257	Pike River at Racine, WI	38.5	26	36.3	20.5	56.4
04093000	Deep River at Lake George Outlet, IN	124	50	116	68.3	59.0
04093500	Burns Ditch at Gary, IN	160	25	156	101	64.8

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04094000	Little Calumet River at Porter, IN	66.2	50	78.0	54.0	69.2
04094500	Salt Creek at McCool, IN	74.6	45	76.7	52.0	67.8
04095300	Trail Creek at Michigan City, IN	54.1	25	76.4	56.5	73.9
04096100	Galena River near LaPorte, IN	17.2	28	26.6	21.5	80.9
04096405	St. Joseph River at Burlington, MI	206	35	178	161	90.7
04096515	South Branch Hog Creek near Allen, MI	48.7	28	43.9	38.4	87.4
04096600	Coldwater Creek near Hodunk, MI	293	26	254	226	88.8
04096900	Nottawa Creek near Athens, MI	162	30	153	136	89.4
04097170	Portage River near Vicksburg, MI	68.2	15	59.9	57.1	95.2
04097540	Prairie River near Nottawa, MI	106	35	98.6	91.8	93.1
04098500	Fawn River near White Pigeon, MI	192	17	157	145	92.6
04099510	Pigeon Creek near Angola, IN	106	50	84.4	76.4	90.6
04099610	Pretty Lake near Stroh, IN	2.0	17	0.48	0.39	80.8
04099750	Pigeon River near Scott, IN	361	29	370	335	90.4
04099808	Lake Elkhart River at Middlebury, IN	97.6	18	102	85.9	84.2
04099850	Pine Creek near Elkhart, IN	31	18	19.8	16.5	83.1
04100222	North Branch Elkhart River at Cosperville, IN	142	26	143	130	91.4

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04100252	Forker Creek near Burr Oak, IN	19.2	28	17.9	14.2	79.6
04100295	Rimmell Branch near Albion, IN	10.7	17	10.7	5.86	54.8
04100377	Solomon Creek near Syracuse, IN	36.1	10	36.2	33.6	92.9
04101800	Dowagiac River at Sumnerville, MI	255	37	301	270	89.6
04102500	Paw Paw River at Riverside, MI	390	46	461	415	90.2
04102700	South Branch Black River near Bangor, MI	83.6	31	107	86.2	80.7
04105000	Battle Creek at Battle Creek, MI	241	64	210	175	83.7
04105700	Augusta Creek near Augusta, MI	38.9	33	45.2	41.9	92.9
04108600	Rabbit River near Hopkins, MI	71.4	32	61.6	47.5	77.2
04108800	Macatawa River near Zeeland, MI	65.8	37	72.1	26.0	36.0
04109000	Grand River at Jackson, MI	174	62	128	106	82.6
04110000	Orchard Creek at Munith, MI	49	11	37.8	28.0	74.0
04111500	Deer Creek near Dansville, MI	16.3	43	11.6	7.26	62.7
04112000	Sloan Creek near Williamston, MI	9.3	43	5.91	3.20	54.1
04112500	Red Cedar River at East Lansing, MI	355	65	215	154	71.6
04112850	Sycamore Creek near Holt, MI	80.6	6	46.8	35.0	74.8
04114500	Looking Glass River near Eagle, MI	281	51	186	159	85.4

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04115000	Maple River at Maple Rapids, MI	434	53	283	224	78.9
04115265	Fish Creek near Crystal, MI	39.7	10	35.0	29.4	84.2
04117000	Quaker Branch near Nashville, MI	7.6	20	6.30	4.61	73.1
04117500	Thornapple River near Hastings, MI	385	53	333	265	79.5
04118500	Rouge River near Rockford, MI	281	39	243	205	84.4
04121000	Muskegon River near Merritt, MI	355	27	230	212	92.1
04121300	Clam River at Vogel Center, MI	243	31	136	121	89.0
04121900	Lake Muskegon River near Morley, MI	138	29	133	116	87.5
04122100	Bear Creek near Muskegon, MI	16.7	32	17.2	14.0	81.6
04122200	White River near Whitehall, MI	406	40	455	413	90.7
04123000	Big Sable River near Freesoil, MI	127	31	139	133	95.5
04123500	Manistee River near Grayling, MI	159	31	184	179	97.0
04125000	Pine River near Le Roy, MI	118	10	89.1	74.3	83.4
04125460	Pine River near Hoxeyville, MI	245	29	288	263	91.2
04126200	Little Manistee River near Freesoil, MI	200	18	174	164	94.5
	STATIONS GAGING STREAMS TRIBUTARY TO LAKE HURON					
04127918	Pine River near Rudyard, MI	184	25	236	177	74.9

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04127997	Sturgeon River at Wolverine, MI	192	54	219	200	91.3
04128990	Pigeon River near Vanderbilt, MI	57.7	46	79.3	69.0	87.0
04129500	Pigeon River at Afton, MI	159	38	140	122	87.4
04131500	Rainy River near Ocqueoc, MI	87.9	27	42.5	34.7	81.6
04132500	Thunder Bay River near Hillman, MI	232	27	215	193	90.0
04134000	North Branch Thunder Bay River near Bolton, MI	184	34	118	92.2	78.0
04135500	Au Sable River at Grayling, MI	110	50	76.4	72.0	94.3
04135600	East Branch Au Sable River at Grayling, MI	76	25	44.2	42.0	95.2
04135700	South Branch Au Sable River near Luzerne, MI	401	28	229	213	93.0
04138000	East Branch Au Gres River at McIvor, MI	84	23	64.1	55.2	86.1
04138500	Au Gres River near National City, MI	169	30	97.2	71.3	73.4
04139000	Houghton Creek near Lupton, MI	29.7	22	51.2	45.5	88.9
04139500	Rifle River at the Ranch, MI	56.8	20	91.5	82.6	90.2
04140000	Prior Creek near Selkirk, MI	21.4	22	17.2	13.3	77.2
04140500	Rifle River at Selkirk, MI	117	31	143	123	86.0
04141000	South Branch Shepards Creek near Selkirk, MI	1.1	26	0.54	0.25	46.0
04141500	West Branch Rifle River near Selkirk, MI	52	11	60.2	49.3	81.9

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04142000	Rifle River near Sterling, MI	320	60	321	259	80.9
04143500	North Branch Kawkawlin River near Kawkawlin, MI	101	30	59.0	38.8	65.8
04144000	Shiawassee River at Byron, MI	368	35	251	202	80.3
04146000	Farmers Creek near Lapeer, MI	55.3	64	32.6	26.2	80.4
04146063	South Branch Flint River near Columbiaville, MI	221	17	185	150	81.0
04147990	Butternut Creek near Genesee, MI	34.7	14	21.0	15.5	74.0
04148200	Swartz Creek near Holly, MI	12.1	19	7.39	6.53	88.3
04148300	Swartz Creek at Flint, MI	115	14	77.0	53.2	69.1
04148440	Thread Creek near Flint, MI	54.4	14	35.6	26.9	75.6
04148720	Brent Run near Montrose, MI	20.8	14	14.6	8.02	54.8
04150000	South Branch Cass River near Cass City, MI	238	31	124	54.4	44.0
04150500	Cass River at Cass City, MI	359	49	231	116	50.4
04152238	South Branch Tobacco River near Beaverton, MI	160	11	133	104	78.6
04152500	Tobacco River at Beaverton, MI	487	33	376	255	67.9
04153500	Salt River near North Bradley, MI	138	36	78.0	39.1	50.2
04154000	Chippewa River near Mt Pleasant, MI	416	65	328	278	84.8
04157500	State Drain near Sebewaing, MI	67.3	14	34.7	11.0	31.6

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04158000	Columbia Drain near Sebewaing, MI	33.9	14	17.2	4.54	26.5
04158500	Pigeon River near Owendale, MI	53.2	29	32.4	18.7	57.9
04159492	Black River near Jeddo, MI	464	52	306	126	41.3
04159900	Mill Creek near Avoca, MI	169	20	95.7	54.4	56.8
04160000	Mill Creek near Abbottsford, MI	208	16	102	58.9	57.9
04160570	North Branch Belle River at Imlay City, MI	18.0	32	12.5	8.73	69.7
04160600	Belle River at Memphis, MI	151	35	94.7	54.2	57.2
04160800	Sashabaw Creek near Drayton Plains, MI	20.9	38	13.3	11.9	89.8
04160900	Clinton River near Drayton Plains, MI	79.2	38	53.1	48.2	90.7
04161100	Galloway Creek near Auburn Heights, MI	17.9	31	11.1	7.56	68.4
04161500	Paint Creek near Lake Orion, MI	38.5	19	24.4	21.1	86.4
04161540	Paint Creek at Rochester, MI	70.9	38	53.6	46.1	86.0
04161580	Stony Creek near Romeo, MI	25.6	33	17.6	14.9	84.6
04161800	Stony Creek near Washington, MI	68.2	39	43.6	37.0	84.9
04163400	Plum Branch at Utica, MI	16.5	32	14.0	7.22	51.7
04163500	Plum Branch near Utica, MI	22.9	12	11.6	5.95	51.2
04164000	Clinton River near Fraser, MI	444	49	390	283	72.4

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04164100	East Pond Creek at Romeo, MI	21.8	39	16.4	14.2	86.4
04164300	East Branch Coon Creek at Armada, MI	13.0	39	7.45	2.72	36.5
04164500	North Branch Clinton River near Mount Clemens, MI	199	49	129	64.3	49.9
04164800	Middle Branch Clinton River at Macomb, MI	41.0	12	30.1	16.8	55.7
	STATIONS GAGING STREAMS TRIBUTARY TO LAKE ERIE					
04166000	River Rouge at Birmingham, MI	33.3	47	20.8	14.1	67.9
04166100	River Rouge at Southfield, MI	87.9	38	68.8	40.0	58.2
04166200	Evans Ditch at Southfield, MI	9.5	39	8.91	3.56	39.9
04166300	Upper River Rouge at Farminton, MI	17.5	39	13.8	8.66	62.9
04166500	River Rouge at Detroit, MI	187	67	125	68.4	54.8
04167000	Middle River Rouge near Garden City, MI	99.9	43	78.7	48.7	61.8
04168000	Lower River Rouge at Inkster, MI	83.2	50	55.8	23.3	41.7
04169500	Huron River at Commerce, MI	57.3	28	37.3	35.3	94.5
04170000	Huron River at Milford, MI	132	49	102	89.8	88.3
04171500	Ore Creek near Brighton, MI	31.0	16	21.2	19.4	91.7
04172000	Huron River near Hamburg, MI	308	46	222	202	91.0
04173500	Mill Creek near Dexter, MI	128	30	79.7	58.9	73.9

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04175340	Stony Creek at Oakville, MI	68.0	11	44.4	28.5	64.2
04175600	River Raisin near Manchester, MI	132	24	105	93.8	89.7
04175700	River Raisin near Tecumseh, MI	267	23	180	149	82.9
04176000	River Raisin near Adrian, MI	463	37	345	261	75.6
04176605	Otter Creek at La Salle, MI	51.0	10	46.2	24.3	52.6
04177000	Ottawa River at Toledo, OH	150	20	130	52.8	40.7
04179500	Cedar Creek near Auburn, IN	87.3	29	68.4	41.4	60.5
04180000	Cedar Creek near Cedarville, IN	270	50	256	147	57.6
04182590	Harbor Ditch at Fort Wayne, IN	21.9	26	18.7	6.16	32.9
04182810	Spy Run at Fort Wayne, IN	14.0	14	18.1	5.92	32.8
04184500	Bean Creek at Powers, OH	206	39	168	109	65.2
04185440	Unnamed tributary to Lost Creek near Farmers, OH	4.2	10	4.01	1.06	26.4
04188500	Eagle Creek near Findlay, OH	55.0	9	43.7	11.2	25.7
04189000	Blanchard River near Findlay, OH	346	50	270	87.9	32.5
04191000	Town Creek near Van Wert, OH	21.2	6	23.8	5.88	24.7
04195000	North Branch Portage River near Bowling Green, OH	45.1	7	42.5	21.3	50.0
04195500	Portage River at Woodville, OH	428	11	334	84.1	25.2

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04196000	Sandusky River near Bucyrus, OH	88.8	30	89.4	29.9	33.5
04196500	Sandusky River near Upper Sandusky, OH	298	42	241	86.8	36.1
04196800	Tymochtee Creek at Crawford, OH	229	6	170	51.6	30.4
04197020	Honey Creek near New Washington, OH	17.0	8	16.1	6.26	39.0
04197100	Honey Creek at Melmore, OH	149	20	132	43.0	32.6
04197170	Rock Creek at Tiffin, OH	34.6	12	28.8	7.71	26.8
04197300	Wolf Creek at Bettsville, OH	66.2	4	53.3	17.2	32.2
04197450	East Branch Wolf Creek near Bettsville, OH	82.4	4	97.5	33.5	34.4
04198500	East Branch Huron River near Norwalk, OH	85.5	10	65.3	22.4	34.3
04199000	Huron River at Milan, OH	371	39	305	107	35.2
04199155	Old Womans Creek at Berlin Road near Huron, OH	22.1	6	22.3	7.37	33.1
04199500	Vermilion River near Vermilion, OH	262	30	258	84.1	32.6
04200000	East Branch Black River at Elyria, OH	217	10	194	48.9	25.2
04202000	Cuyahoga River at Hiram Rapids, OH	151	6	162	113	69.5
04207200	Tinkers Creek at Bedford, OH	83.9	29	134	64.0	47.8
04209000	Chagrin River at Willoughby, OH	246	6	410	173	42.3
04209500	Grand River near North Bristol, OH	85.4	4	88.4	29.4	33.2

Table 1. Ground-water component of streamflow for selected U.S. Geological Survey gaging stations in the Great Lakes Basin--continued

USGS Station number	Station name	Drainage area (square miles)	Years of record	Average streamflow (cubic feet per second)	Average ground-water component of streamflow (cubic feet per second)	Average ground-water component of streamflow (percent)
04210000	Phelps Creek near Windsor, OH	25.6	15	35.4	10.3	29.1
04210500	Grand River near Rome, OH	251	4	274	109	39.9
04211000	Rock Creek near Rock Creek, OH	69.2	23	75.4	21.3	28.2
04212500	Ashtabula River near Ashtabula, OH	121	28	160	53.6	33.6
04213000	Conneaut Creek at Conneaut, OH	175	46	290	109	37.7
04213040	Raccoon Creek near West Springfield, PA	2.5	26	3.39	1.63	48.0
04213075	Brandy Run near Girard, PA	4.4	8	7.16	3.65	51.0
04213500	Cattaraugus Creek at Gowanda, NY	436	50	749	426	56.8
04214500	Buffalo Creek at Gardenville, NY	142	50	208	93.2	44.9
04215000	Cayuga Creek near Lancaster, NY	96.4	51	135	55.7	41.3
04215500	Cazenovia Creek at Ebenezer, NY	135	50	237	104	43.9
	STATIONS GAGING STREAMS TRIBUTARY TO LAKE ONTARIO					
04220262	Northup Creek at North Greece, NY	11.7	8	13.4	8.72	65.0
04232050	Irondequoit Creek, Rochester, NY	142	7	139	93.5	67.2
04232100	Sterling Creek at Sterling, NY	44.4	37	66.8	45.7	68.4
04250750	Sandy Creek at Adams, NY	128	37	277	166	59.8

Appendix 1. Computation of Indirect Ground-Water Discharge to the Great Lakes

Lake Superior

Basin Supply Item*	Explanation
$Runoff_{Lake.S} := 24.16 \cdot in$	Runoff is total streamflow from land areas within the basin.
$Precip_{Lake.S} := 31.14 \cdot in$	Precip is overlake precipitation
$Evap_{Lake.S} := 22.45 \cdot in$	Evap is evaporation from the lake surface.
$NBS_{Lake.S} := 32.86 \cdot in$	NBS is net basin supply computed as Runoff + Precip - Evap.

*Based on monthly data from 1950 to 1990 as reported by Croley and Hunter (1994). All basin supply items are expressed as inches over the surface area of the corresponding lake. "S" denotes Superior.

Physical Characteristics

$Area_{Lake.S} := 31700 \cdot mi^2$ Area of the lake surface.

$Area_{Land.S} := 49300 \cdot mi^2$ Area of the land surface draining into the lake.

$Area_{Basin.S} := Area_{Lake.S} + Area_{Land.S}$

The average ground-water component of streamflow for runoff from the Lake Superior basin (Groundwater.Percent.S) is based on hydrograph separation analysis of streamflow records from 15 USGS gaging stations.

$Groundwater_{Percent.S} := 74.85 \cdot \%$

Results of Subdividing Runoff into Indirect-Ground Water and Surface-Runoff Components

$Runoff_{Lake.IndirectGroundWater.S} := Runoff_{Lake.S} \cdot Groundwater_{Percent.S}$

$Runoff_{Lake.IndirectGroundWater.S} = 18.084 \cdot in$

$Runoff_{Lake.SurfaceRunoff.S} := Runoff_{Lake.S} \cdot \left(1 - Groundwater_{Percent.S}\right)$

$Runoff_{Lake.SurfaceRunoff.S} = 6.076 \cdot in$

"Runoff$_{Lake}$" refers to the volume of runoff expressed in lake-area equivalent inches.

Annual runoff from land surface.

$Runoff_{Land.IndirectGroundWater.S} := Runoff_{Lake.S} \cdot Area_{Lake.S} \cdot Groundwater_{Percent.S} \cdot Area_{Land.S}^{-1}$

$Runoff_{Land.IndirectGroundWater.S} = 11.628 \cdot in$

$Runoff_{Land.SurfaceRunoffirectSurface.S} := Runoff_{Lake.S} \cdot Area_{Lake.S} \cdot \left(1 - Groundwater_{Percent.S}\right) \cdot Area_{Land.S}^{-1}$

$Runoff_{Land.SurfaceRunoffirectSurface.S} = 3.907 \cdot in$

"Runoff$_{Land}$" refers to the volume of runoff expressed in basin land-area equivalent inches.

Appendix 1. Computation of Indirect Ground-Water Discharge to the Great Lakes--Continued

Lake Michigan

Basin Supply Item*	Explanation
$Runoff_{Lake.M} := 25.11 \cdot in$	Runoff is total streamflow from land areas within the basin.
$Precip_{Lake.M} := 32.21 \cdot in$	Precip is overlake precipitation
$Evap_{Lake.M} := 25.18 \cdot in$	Evap is evaporation from the lake surface.
$NBS_{Lake.M} := 32.14 \cdot in$	NBS is net basin supply computed as Runoff + Precip - Evap.

*Based on monthly data from 1950 to 1990 as reported by Croley and Hunter (1994). All basin supply items are expressed as inches over the surface area of the corresponding lake. "M" denotes Michigan.

Physical Characteristics

$Area_{Lake.M} := 22300 \cdot mi^2$ Area of the lake surface.

$Area_{Land.M} := 45600 \cdot mi^2$ Area of the land surface draining into the lake.

$Area_{Basin.M} := Area_{Lake.M} + Area_{Land.M}$

The average ground-water component of streamflow for runoff from the Lake Michigan basin (Groundwater.Percent.M) is based on hydrograph separation analysis of streamflow records from 64 USGS gaging stations.

$Groundwater_{Percent.M} := 78.68 \cdot \%$

Results of Subdividing Runoff into Indirect-Ground Water and Surface-Runoff Components

$Runoff_{Lake.IndirectGroundWater.M} := Runoff_{Lake.M} \cdot Groundwater_{Percent.M}$

$Runoff_{Lake.IndirectGroundWater.M} = 19.757 \cdot in$

$Runoff_{Lake.SurfaceRunoffirectSurface.M} := Runoff_{Lake.M} \cdot \left(1 - Groundwater_{Percent.M}\right)$

$Runoff_{Lake.SurfaceRunoffirectSurface.M} = 5.353 \cdot in$

"$Runoff_{Lake}$" refers to the volume of runoff expressed in lake-area equivalent inches.

Annual runoff from land surface.

$Runoff_{Land.IndirectGroundWater.M} := Runoff_{Lake.M} \cdot Area_{Lake.M} \cdot Groundwater_{Percent.M} \cdot Area_{Land.M}^{-1}$

$Runoff_{Land.IndirectGroundWater.M} = 9.662 \cdot in$

$Runoff_{Land.SurfaceRunoffirectSurface.M} := Runoff_{Lake.M} \cdot Area_{Lake.M} \cdot \left(1 - Groundwater_{Percent.M}\right) \cdot Area_{Land.M}^{-1}$

$Runoff_{Land.SurfaceRunoffirectSurface.M} = 2.618 \cdot in$

"$Runoff_{Land}$" refers to the volume of runoff expressed in basin land-area equivalent inches.

Appendix 1. Computation of Indirect Ground-Water Discharge to the Great Lakes--Continued

Lake Huron

Basin Supply Item*	Explanation
$Runoff_{Lake.H} := 45.78 \cdot in$	Runoff is total streamflow from land areas within the basin.
$Precip_{Lake.H} := 33.43 \cdot in$	Precip is overlake precipitation
$Evap_{Lake.H} := 24.20 \cdot in$	Evap is evaporation from the lake surface.
$NBS_{Lake.H} := 55.00 \cdot in$	NBS is net basin supply computed as Runoff + Precip - Evap.

*Based on monthly data from 1955 to 1990 as reported by Croley and Hunter (1994). All basin supply items are expressed as inches over the surface area of the corresponding lake. "H" denotes Huron.

Physical Characteristics

$Area_{Lake.H} := 23000 \cdot mi^2$ Area of the lake surface.

$Area_{Land.H} := 51700 \cdot mi^2$ Area of the land surface draining into the lake.

$Area_{Basin.H} := Area_{Lake.H} + Area_{Land.H}$

The average ground-water component of streamflow for runoff from the Lake Huron basin (Groundwater.Percent.H) is based on hydrograph separation analysis of streamflow records from 56 USGS gaging stations.

$Groundwater_{Percent.H} := 71.82 \cdot \%$

Results of Subdividing Runoff into Indirect-Ground Water and Surface-Runoff Components

$Runoff_{Lake.IndirectGroundWater.H} := Runoff_{Lake.H} \cdot Groundwater_{Percent.H}$

$Runoff_{Lake.IndirectGroundWater.H} = 32.879 \cdot in$

$Runoff_{Lake.SurfaceRunoffirectSurface.H} := Runoff_{Lake.H} \cdot \left(1 - Groundwater_{Percent.H}\right)$

$Runoff_{Lake.SurfaceRunoffirectSurface.H} = 12.901 \cdot in$

"Runoff.$_{Lake}$" refers to the volume of runoff expressed in lake-area equivalent inches.

Annual runoff from land surface.

$Runoff_{Land.IndirectGroundWater.H} := Runoff_{Lake.H} \cdot Area_{Lake.H} \cdot Groundwater_{Percent.H} \cdot Area_{Land.H}^{-1}$

$Runoff_{Land.IndirectGroundWater.H} = 14.627 \cdot in$

$Runoff_{Land.SurfaceRunoffirectSurface.H} := Runoff_{Lake.H} \cdot Area_{Lake.H} \cdot \left(1 - Groundwater_{Percent.H}\right) \cdot Area_{Land.H}^{-1}$

$Runoff_{Land.SurfaceRunoffirectSurface.H} = 5.739 \cdot in$

"Runoff.$_{Land}$" refers to the volume of runoff expressed in basin land-area equivalent inches.

Appendix 1. Computation of Indirect Ground-Water Discharge to the Great Lakes--Continued

Lake Erie

Basin Supply Item*	Explanation
$Runoff_{Lake.E} := 31.63 \cdot in$	Runoff is total streamflow from land areas within the basin.
$Precip_{Lake.E} := 36.41 \cdot in$	Precip is overlake precipitation
$Evap_{Lake.E} := 35.20 \cdot in$	Evap is evaporation from the lake surface.
$NBS_{Lake.E} := 32.84 \cdot in$	NBS is net basin supply computed as Runoff + Precip - Evap.

*Based on monthly data from 1950 to 1990 as reported by Croley and Hunter (1994). All basin supply items are expressed as inches over the surface area of the corresponding lake. "E" denotes Erie.

Physical Characteristics

$Area_{Lake.E} := 9910 \cdot mi^2$	Area of the lake surface.
$Area_{Land.E} := 30140 \cdot mi^2$	Area of the land surface draining into the lake.

$Area_{Basin.E} := Area_{Lake.E} + Area_{Land.E}$

The average ground-water component of streamflow for runoff from the Lake Erie basin (Groundwater.Percent.E) is based on hydrograph separation analysis of streamflow records from 56 USGS gaging stations.

$Groundwater_{Percent.E} := 47.82 \cdot \%$

Results of Subdividing Runoff into Indirect-Ground Water and Surface-Runoff Components

$Runoff_{Lake.IndirectGroundWater.E} := Runoff_{Lake.E} \cdot Groundwater_{Percent.E}$

$Runoff_{Lake.IndirectGroundWater.E} = 15.125 \cdot in$

$Runoff_{Lake.SurfaceRunoffirectSurface.E} := Runoff_{Lake.E} \cdot \left(1 - Groundwater_{Percent.E}\right)$

$Runoff_{Lake.SurfaceRunoffirectSurface.E} = 16.505 \cdot in$

"$Runoff_{Lake}$" refers to the volume of runoff expressed in lake-area equivalent inches.

Annual runoff from land surface.

$Runoff_{Land.IndirectGroundWater.E} := Runoff_{Lake.E} \cdot Area_{Lake.E} \cdot Groundwater_{Percent.E} \cdot Area_{Land.E}^{-1}$

$Runoff_{Land.IndirectGroundWater.E} = 4.973 \cdot in$

$Runoff_{Land.SurfaceRunoffirectSurface.E} := Runoff_{Lake.E} \cdot Area_{Lake.E} \cdot \left(1 - Groundwater_{Percent.E}\right) \cdot Area_{Land.E}^{-1}$

$Runoff_{Land.SurfaceRunoffirectSurface.E} = 5.427 \cdot in$

"$Runoff_{Land}$" refers to the volume of runoff expressed in basin land-area equivalent inches.

Appendix 1. Computation of Indirect Ground-Water Discharge to the Great Lakes--Continued

Lake Ontario

Basin Supply Item*	Explanation
$Runoff_{Lake.O} := 64.08 \cdot in$	Runoff is total streamflow from land areas within the basin.
$Precip_{Lake.O} := 34.14 \cdot in$	Precip is overlake precipitation
$Evap_{Lake.O} := 25.40 \cdot in$	Evap is evaporation from the lake surface.
$NBS_{Lake.O} := 72.82 \cdot in$	NBS is net basin supply computed as Runoff + Precip - Evap.

*Based on monthly data from 1950 to 1990 as reported by Croley and Hunter (1994). All basin supply items are expressed as inches over the surface area of the corresponding lake. "O" denotes Ontario.

Physical Characteristics

$Area_{Lake.O} := 7340 \cdot mi^2$ Area of the lake surface.

$Area_{Land.O} := 24720 \cdot mi^2$ Area of the land surface draining into the lake.

$Area_{Basin.O} := Area_{Lake.O} + Area_{Land.O}$

The average ground-water component of streamflow for runoff from the Lake Ontario basin (Groundwater.Percent.O) is based on hydrograph separation analysis of streamflow records from 4 USGS gaging stations.

$Groundwater_{Percent.O} := 65.10 \cdot \%$

Results of Subdividing Runoff into Indirect-Ground Water and Surface-Runoff Components

$$Runoff_{Lake.IndirectGroundWater.O} := Runoff_{Lake.O} \cdot Groundwater_{Percent.O}$$

$$Runoff_{Lake.IndirectGroundWater.O} = 41.716 \cdot in$$

$$Runoff_{Lake.SurfaceRunoffirectSurface.O} := Runoff_{Lake.O} \cdot \left(1 - Groundwater_{Percent.O}\right)$$

$$Runoff_{Lake.SurfaceRunoffirectSurface.O} = 22.364 \cdot in$$

"Runoff.$_{Lake}$" refers to the volume of runoff expressed in lake-area equivalent inches.

Annual runoff from land surface.

$$Runoff_{Land.IndirectGroundWater.O} := Runoff_{Lake.O} \cdot Area_{Lake.O} \cdot Groundwater_{Percent.O} \cdot Area_{Land.O}^{-1}$$

$$Runoff_{Land.IndirectGroundWater.O} = 12.387 \cdot in$$

$$Runoff_{Land.SurfaceRunoffirectSurface.O} := Runoff_{Lake.O} \cdot Area_{Lake.O} \cdot \left(1 - Groundwater_{Percent.O}\right) \cdot Area_{Land.O}^{-1}$$

$$Runoff_{Land.SurfaceRunoffirectSurface.O} = 6.64 \cdot in$$

"Runoff.$_{Land}$" refers to the volume of runoff expressed in basin land-area equivalent inches.