THE SIGNIFICANCE OF GROUND WATER IN THE HOUGHTON LAKE DRAINAGE BASIN

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

TED L. SWEARINGEN

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THE SIGNIFICANCE OF GROUND WATER IN THE HOUGHTON LAKE DRAINAGE BASIN

By

Ted Lee Swearingen

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
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CHAPTER I

INTRODUCTION

Many of the lakes of Michigan have been considered as being spring fed (Door & Eschman, 1970). That is, a significant proportion of the water entering the lake basin is from ground water. Furthermore, where that ground water passes through populated areas (the occupied zone) it has been assumed that waste materials are transported to the lake (Ketelle & Uttormark, 1971). The State of Michigan has tentatively, identified Houghton Lake as being such a lake with possible associated ground-water contamination.

From September 1971 to August 1972 the flux of water through the Houghton Lake system was monitored with the purpose of developing a water budget for the lake and evaluating the contribution by ground water to the system. In addition, that portion of the ground water that flowed into the lake from adjacent populated areas was determined by relating hydraulic conductivity of the soils to a depth of twenty feed around the lake shore to potentiometric slope of the water table. This allowed characterization of that proportion of the ground water that has the potential of chemical contamination of the lake system. Ground water that enters the lake from depths greater than twenty feet is not likely to contain nutrient concentrations higher than background levels (Childs, 1972).

Houghton Lake is the largest inland lake in Michigan, and is located in the north-central section of the lower peninsula in Roscommon County. The lake basin was formed from the melting of an ice block that had broken away or had been separated from the retreiting glacier (Martin, 1958). There are three distinct types of glacial deposits in the area: (1) ground moraine, (2) marginal moraine, and (3) outwash. These deposits have resulted in a wide range of soil types with varying hydraulic conductivities. Consequently, the volumes of ground water entering the lake vary considerably from one area to another. The lake proper occupies an area of approximately 19,600 acres or 31.0 square miles, has an average depth of 8.7 feet, thermally stratifies during the summer months and is usually frozen over four to five months each year. The Houghton Lake drainage basin has an area of 218 square miles at the Muskegon River outlet (Miller and Thompson, 1970). Of the 218 square miles, the Higgins Lake drainage basin occupies 58 square miles, the Houghton Lake surface 31 square miles, and the major and minor tributaries to Houghton Lake receive runoff from 187 square miles which includes the Higgins Lake basin.

A water budget was determined for Houghton Lake by using the mass-balance method. The budget includes calculations for runoff, over-water precipitation, evaporation from the lake surface, outflow through the Muskegon River, and is solved for the unknown ground water. The budget covers the period from September 1971 through August 1972, with all calculations made on a monthly basis. This method results in an estimate of the total volume of ground water entering Houghton Lake.

Flow-net analysis was used to determine the volume of ground water entering Houghton Lake through the upper twenty feet of sediment adjacent to the shoreline. Darcy's Law was used to solve for that volume of ground water. Consequently, a water-table potentiometric map and a flow net for the Houghton Lake drainage basin were required. A fence diagram was constructed and designed for depicting soil and sediment hydraulic conductivity to a depth of twenty feet along the shoreline of Houghton Lake. The volumes of ground water entering the lake through the twenty feet were determined for specified soil groups. The soil groups are based on similarities in phosphorus adsorption capacities (Erickson and Schneider, 1972) and hydraulic conductivities of the soils.

The ultimate goal of this thesis is to generate reliable methodology that can be used to other lakes in Michigan, and to determine the significance of the volumes of ground water entering Houghton Lake.

CHAPTER II

HOUGHTON LAKE WATER BUDGET

Total ground water input to Houghton Lake was estimated by establishing a water budget for the lake. The general mass balance equation for a water budget is

$$I + P \pm G - O - E - T = \Delta S. \qquad (1)$$

Where; I equals the volume of runoff entering the lake from inflowing tributaries, P the precipitation falling on the lake surface, G the volume of ground water entering and leaving Houghton Lake, O represents the volume of discharge from Houghton Lake through the Muskegon River outlet, E the evaporation directly from the lake surface, T the transpiration from aquatic macrophytes, ΔS the change in lake level. Values can be determined for all parameters except ground water G, therefore, the equation can be reconstructed to solve for ground water and is stated as

$$O + E + T + \Delta S - P - I = \pm G. \qquad (2)$$

The calculation of $\pm G$ gives the net contribution by ground water to the lake after ground-water loss through interbasin flow.

Major and Minor Tributaries and Outflow

There are four major tributaries flowing into Houghton Lake (Figure 1), The Cut, Denton Creek, Knappen Creek and Spring Brook. The Muskegon River is the only surface water outlet from the lake. Discharge data are minimal for the major tributaries and on the Muskegon River near the outlet, therefore, to obtain values for runoff I, discharge correlation curves had to be determined for each major stream. Discharge correlations (Figures 2-6, see Appendix) for estimating the monthly discharge (Tables 1 and 2) for each major stream were determined by plotting available discharge data (United States Geological Survey, 1970) for the above streams against the continuously monitored Merritt (Gage no. 1210) and Evart (Gage no. 1215) on the Muskegon River (Figure 7). The mean discharge for the major tributaries was then determined from the correlations by plotting the known mean monthly discharge at the Evart gage.

Four minor tributaries and twenty-eight drains were identified (State of Michigan, 1973) in the Houghton Lake drainage basin. Names and locations of these tributaries are listed in Appendix Table A and on Figure 1. The monthly and annual volumes of water which the drains and minor tributaries contributed as a total to Houghton Lake were determined indirectly by correlating the volume of discharge against drainage-basin area for gaging stations on

Figure 1.--Location of drains and tributaries flowing into Houghton Lake and the Muskegon River Outlet.

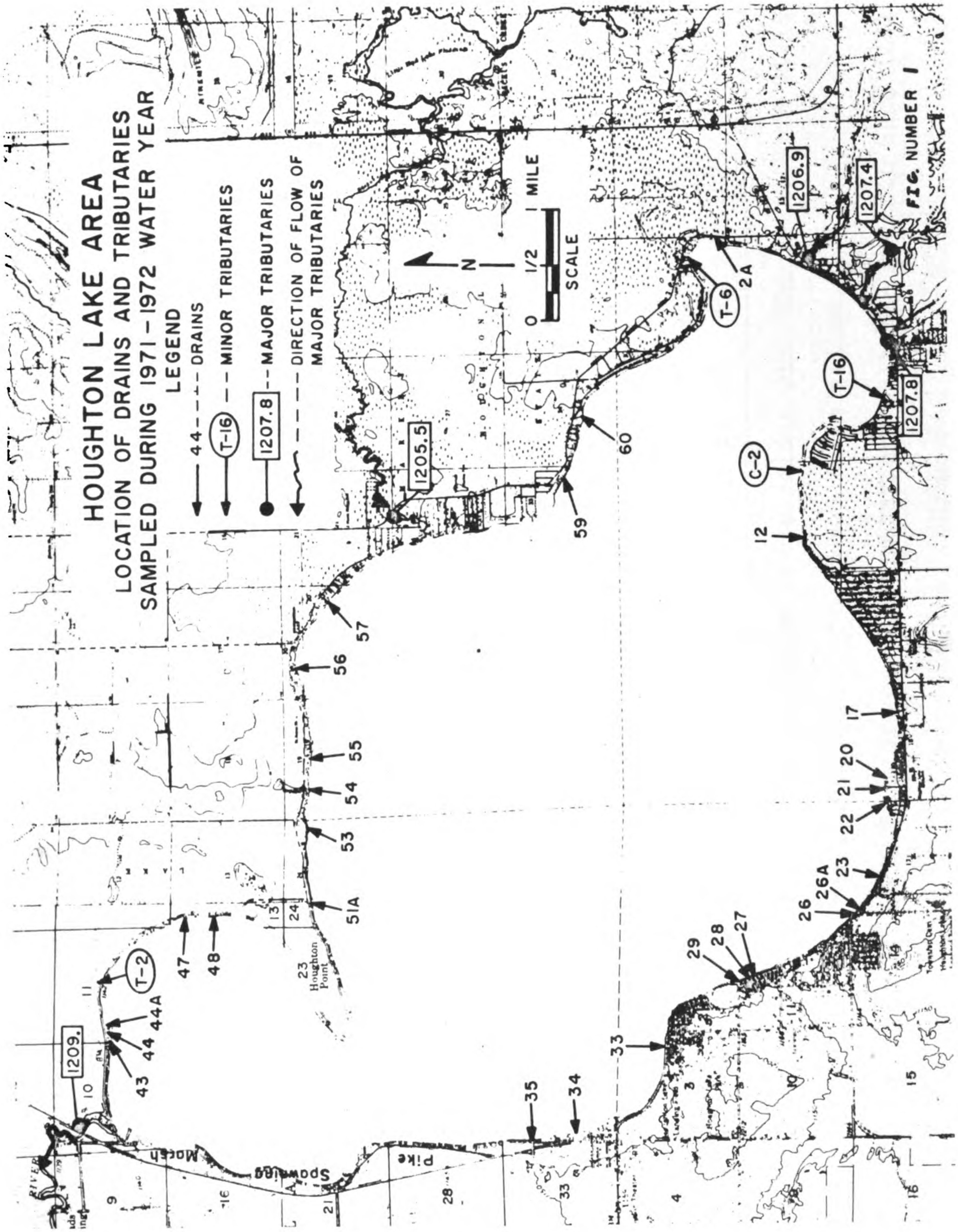

HOUGHTON LAKE AREA
LOCATION OF DRAINS AND TRIBUTARIES
SAMPLED DURING 1971-1972 WATER YEAR
LEGEND
44 — DRAINS
T-16 — MINOR TRIBUTARIES
1207.8 — MAJOR TRIBUTARIES
DIRECTION OF FLOW OF MAJOR TRIBUTARIES
N
0 1/2 1 MILE
SCALE
1205.5
1209.
1206.9
1207.4
1207.8
T-2
T-6
T-16
C-2
2A
11
12
17
20
21
22
23
26
26A
27
28
29
33
34
35
43
44
44A
47
48
51A
53
54
55
56
57
59
60
Houghton Point
Spawning
Pike
Marsh
RIVER

FIG. NUMBER 1

TABLE 1.--Discharge in Cubic Feet per Second of Major Tributaries into Houghton Lake.

		Inflowing Based on Evart Gage[1]						Outflowing Based on Means at Merritt Gage[3]	
Month	Year	Evart	Denton Creek	Spring Brook	Knappen Creek	The Cut	Minor[2] Streams	Merritt	Musk. R. at the Outlet
Sept.	1971	435	1.1	.30	1.4	29	11	78.7	64
Oct.	1971	460	1.4	.35	1.55	31	4	62	51
Nov.	1971	483	1.6	.37	1.6	32.5	16	54.4	47
Dec.	1971	963	8.6	.8	3.9	66	15	144	105
Jan.	1972	648	3.2	.5	2.3	42	4	85.5	70
Feb.	1972	572	2.3	.43	2.0	37	8	76.8	62
March	1972	858	6.6	.72	3.4	58	29	202	144
April	1972	2,568	78	2.8	13	175	60	601.7	370
May	1972	1,521	27	1.5	7	105	16	540	330
June	1972	660	3.3	.5	2.3	42	12	196	140
July	1972	530	1.9	.4	1.8	35	11	143	105
Aug.	1972	673	3.4	.52	2.4	43	9	107	84

[1] Calculations made from Discharge Correlations with the Evart Gage (1215)

[2] Calculated from Drainage Area-Discharge Correlations.

[3] Calculation made from Discharge Correlations with the Merritt Gage (1210).

TABLE 2.--Discharge in Acre Feet per Year of Major Tributaries into Houghton Lake.

Month	Year	Denton Creek	Spring Brook	Knappen Creek	The Cut	Minor Tribs.	Musk. R. at the Outlet
Sept.	1971	65.5	17.9	83.3	1,730	655	3,940
Oct.	1971	86.1	21.5	95.3	1,910	245	3,140
Nov.	1971	95.2	22.8	98.4	1,930	984	2,800
Dec.	1971	529.	49.2	240.	4,060	922	6,460
Jan.	1972	197.	30.7	141.	2,580	245	4,300
Feb.	1972	132.	24.7	115.	2,610	460	3,570
March	1972	406.	44.3	209.	3,570	1,780	8,850
April	1972	4,641.	166.6	773.6	10,410	3,570	22,020
May	1972	1,660.	92.23	430.4	9,220	984	2,029
June	1972	203.	29.8	137.	2,500	714	8,330
July	1972	117.	24.6	111.	2,150	676	6,460
Aug.	1972	209.	32.0	148.	2,640	533	5,160

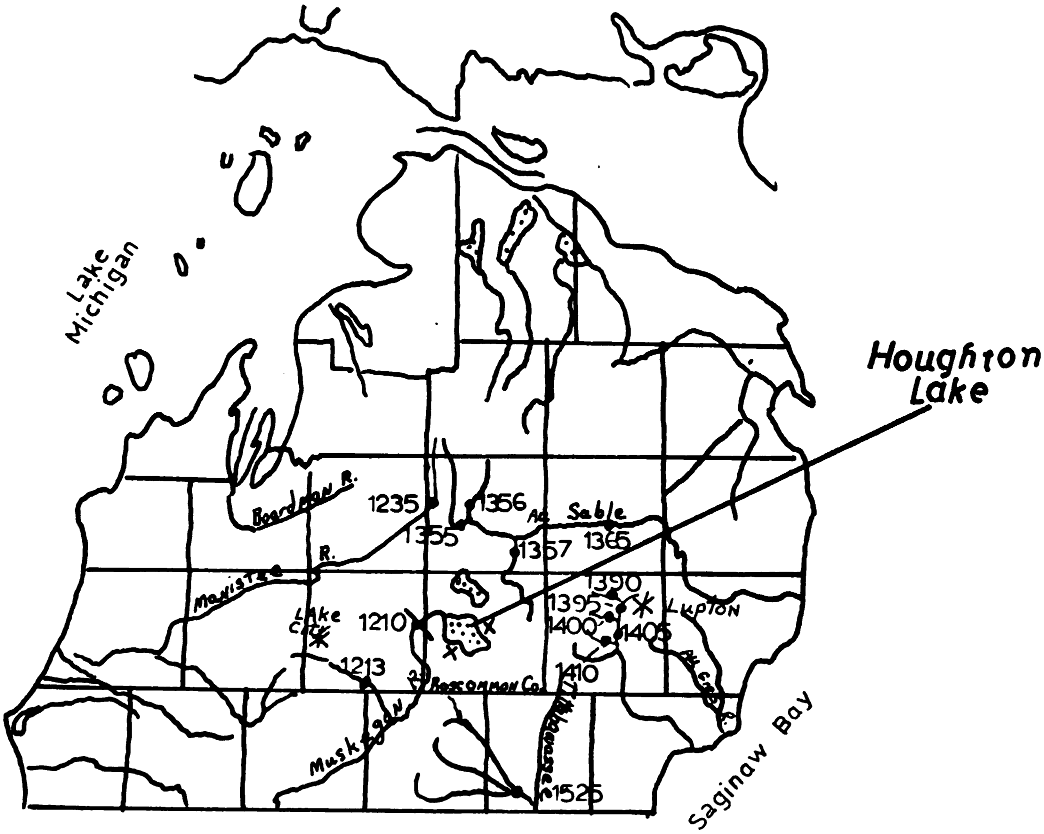


Figure 7.--Map showing identification number and location of U.S.G.S. gaging stations, precipitation stations,[x] and evaporation pans.*

rivers in the Houghton Lake vicinity. The following procedure was used to estimate runoff from the minor tributaries and drains:

1. Correlations were made (Figures 8-20, see Appendix) of drainage area versus mean annual and monthly discharge (Table 3) for gages on rivers and streams within approximately 50 miles of Houghton Lake (Figure 1).

2. The drainage area of the minor tributaries was determined from the flow net (Figure 21, see page 28) and equals approximately 22 square miles.

3. The mean annual discharge correlation was based on discharge data for the water year 1970. Variations in mean discharge occur each year. Gage data for the water year 1971 were not available at the time of this thesis for streams outside of the Houghton Lake area.

The correlations of drainage basin area versus discharge and the discharge correlations in all cases have a statistical significance of 0.01 = P.

The major tributaries contributed 56,800 acre feet of water to the lake during the annual period from September 1971 through August 1972. The minor tributaries and drains added another 11,700 acre feet of water to the lake surface, for a total of 68,500 acre feet. This volume represents the largest single volume of water entering the lake.

Total outflow through the Muskegon River outlet, near Houghton Heights, was approximately 95,300 acre feet for the annual period.

TABLE 3.--Drainage Area and Discharge Data (in cfs) Derived from United States Geological Survey Records and Used in the Drainage Area-Discharge Correlations (Oct., 1970 - Sept., 1971).

U.S.G.S. Station No.	Area Sq. Miles	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.
1210	355	214	356	423	311	341	544	747	481	282	127	124	78.7
1213	243	78.4	152	157	115	122	172	393	194	99.3	76.7	79.5	75.9
1235	159	191	192	192	170	177	188	264	228	205	192	187	183
1355	110	76.9	83.5	85.2	70.3	75	82.8	145	107	87.1	73.5	73.5	67.8
1356	76	51.4	55.9	59.2	43.4	44.3	52.4	115	74.8	56.4	49.1	49.4	43.8
1357	401	211	307	302	217	222	304	576	323	229	154	152	138
1365	1,100	1050	1224	1205	998	1049	1224	2241	1450	1142	926	927	873
1390	29.7	47.3	68	59.2	42.8	51.7	61.9	125	57.1	50.5	40.6	39	38.5
1395	56.8	86.1	125	105	82.3	94.8	117	225	97.5	84.3	74.1	66.8	62.5
1400	21.4	14.6	33.4	27.9	15.5	21	35.3	77.3	21	13.3	8.57	7.05	7.48
1405	117	120	212	176	120	157	216	453	160	120	92.1	88.7	83.5
1410	1.15	.23	.98	.73	.27	.81	1.78	3.85	.26	.12	.086	.080	.082
1525	487	314	479	442	323	476	779	1206	348	258	169	157	174

Precipitation

Daily precipitation measurements for Houghton Lake were taken by the United States Department of Commerce, National Weather Service. Data for precipitation (P) used in equation (2) were obtained from the climatological station at Houghton Lake WSO AP (airport) and the Houghton Lake 3 NW station. The Houghton Lake 3 NW station is located on the southwest side of Houghton Lake in Houghton Heights (Figure 7), and the Houghton Lake WSO AP station is located at the Roscommon County Airport to the northeast of the lake. Because these two stations are located on opposite sides of this large inland lake, an average (Table 4) of the two stations gives a good estimate of precipitation falling on the lake.

Houghton Lake was frozen from November 22 to December 14, 1971, and again from December 15, 1971 to April 29, 1972. When the lake was covered with ice, precipitation was not included in the monthly calculation since the water that was stored on the ice had no way of entering the lake. During periods of melting the total precipitation that had fallen on the ice up to that time was included within the month of the melt.

Approximately 27.7 inches of precipitation fell at the Houghton Lake 3 NW station and 24.6 inches fell at the Houghton Lake WSO AP station during the period of September 1971 through August 1972. The average over-water

TABLE 4.--Precipitation on Houghton Lake.

		Houghton Lake 3 NW				Houghton Lake WSO AP				
Month	Year	Ppct./in.	Ppct. Held On Ice	Total For Mo.	Acre Ft. Ppct.	Ppct. Per In.	Ppct. Held On Ice	Total For Mo.	Ppct. Add to H.L. Acre/Ft.	Avg. Acre/Ft.
Sept.	1971	2.05		2.05	3,350	1.20		1.20	1,960	2,650
Oct.	1971	.49		.49	800	.47		.47	770	780
Nov.	1971	1.11		1.11	1,810	1.22		1.22	1,990	1,900
Nov. (22)	1971		.51				.74			
Dec.		M*	2.06	2.57	4,200	M	1.96	2.70	4,410	4,300
Dec. (15)	1971		2.73				2.52			
Jan.	1972	Lake Frozen	.68	0	0	Lake Frozen	.82	0	0	0
Feb.	1972	This	1.16	0	0	This	.99	0	0	0
Mar.	1972	Period	2.46	0	0	Period	2.36	0	0	0
Apr.	1972		1.14	0	0		1.40	0	0	0
Apr. (30)	1972	M		8.17	13,300	M		8.09	13,200	13,300
May.	1972	1.93		1.93	3,150	1.79		1.79	2,920	3,040
June	1972	2.14		2.14	3,500	2.00		2.00	3,270	3,380
July	1972	3.31		3.31	5,710	2.52		2.52	4,120	4,760
Aug.	1972	5.92		5.92	9,670	4.63		4.63	7,560	8,620
TOTAL		1695	10.74	27.69	45,200	13.83	1079	24.62	40,200	43,000

*M = Lake ice melted.

precipitation added to the lake, calculated from the two stations, was 26.15 inches or 43,000 acre feet.

Evaporation

Evaporation (E) (Table 5) from the surface of Houghton Lake during the period September, 1971 through August, 1972 was determined by using Class A Pan evaporation measurements (United States Department of Commerce, 1959) made by the National Weather Service at Lupton and Lake City, Michigan. The Lake City Pan gage is located west of Houghton Lake, and the Lupton gage to the northeast (Figure 7). An average calculation was made using both gages in order to reduce the possibility of error at one of the stations. Class A Pan measurements are available from these two stations for the months of May through October for each year. Pan data were not available for the winter months, therefore, an estimate had to be made for that period. Class A Pan measurements for the six months of May through October are believed to represent 80% of the total evaporation for the entire year (United States Department of Commerce, 1959) in the Houghton Lake area. This percentage is based on the average temperatures for the area, number of cloudy days, and latitude. The estimated evaporation was divided equally for the months with no available evaporation data. Evaporation for January through April was accumulated and used in the month of April, in order to

TABLE 5.--Evaporation from Houghton Lake (inches).

		Lupton Pan Gage				Lake City Pan Gage					
Month	Year	Known Evap.	Est. Evap.	Est. Ann. Evap.	(Ea X .8) Lake Evap.	Known Evap.	Est. Evap.	Est. Ann. Evap.	(Ea X .8) Lake Evap.	Avg. Two Gages	Conv. to Acre Feet
Sept.	1971	3.00			2.40	3.50			2.80	2.60	4,250
Oct.	1971	1.54			1.23	2.00			1.60	1.42	2,310
Nov.	1971		1.17		.94		1.27		1.08	.91	1,600
Dec.	1971		1.00		.80		1.27		1.08	.91	1,490
Jan.*	1972		1.00		.80		1.27		1.08	.91	1,490
Feb.	1972		1.00		.80		1.27		1.08	.91	1,490
Mar.	1972		1.00		.80		1.27		1.08	.91	1,490
Apr.	1972		1.00=4.0		.80 3.2		1.27 5.08		1.08 4.32	.91	1,490 5960
May	1972	6.37			5.10	7.81			6.25	5.67	9,260
June	1972	4.45			3.56	5.62			4.45	4.03	6,580
July	1972	5.70			4.56	7.11			5.69	5.12	8,370
Aug.	1972	3.60			2.88	4.48			3.58	3.23	5,280
Total		24.7	6.17	30.8	24.7	30.50	7.63	38.20	30.50	27.60	45,100

*Evaporation for the month of Jan. through April included in April calculation.

correspond with precipitation data. Evaporation for months with partial data were extrapolated for the whole month on a percentage basis. Pan evaporation cannot be used directly for lake evaporation, since there are differences in heat transfer between the pan and the open lake system. Lake evaporation for the Houghton Lake area is estimated by multiplying the Class A Pan measurement by 0.8 (United States Department of Commerce, 1959).

During the annual period from September 1971 through August 1972 approximately 45,100 acre-feet (2.3 feet) of water evaporated from the surface of Houghton Lake. There was a net loss, considering precipitation and evaporation, of 2,100 acre feet of water from the surface of Houghton Lake during the annual period.

Transpiration from aquatic macrophytes has not been included in the water budget. It is believed that, due to; (1) the large volume of evaporation from the lake, (2) the relatively small area which the plants occupy, (3) the vertical type of leaves on the majority of the plants, and (4) the short duration each year that the stems are above lake level, that transpiration is likely to be a relatively minor source of water loss from the lake.

Change in Storage

The water level in Houghton Lake may fluctuate from month to month because of adjustments made on the stop logs at the Reedsburg Dam (Figure 7) on the Muskegon River. The change in storage within the lake can be determined from readings taken at the staff gage at the outlet of the Muskegon River. The water levels were obtained (Table 6) from United States Geological Survey continuously monitored by gage recordings at the Muskegon River Outlet. The monthly change in storage in Houghton Lake was significant. For example, between December 1, 1971 and January 1, 1972 the lake level rose 15,000 acre-feet or more than 0.75 feet. Between May 1, 1972 and June 1, 1972 the lake level was lowered 12,000 acre-feet or approximately 0.66 feet. The net change in lake level from September 1, 1971 to September 1, 1972 was a rise of 13,000 acre-feet. Therefore, utilizing equation (2) without an account of change in storage would have resulted in a volume for ground water that was 13,000 acre-feet less than the actual figure obtained.

Ground Water

The total volume of ground water entering Houghton Lake from September, 1971, through August, 1972, was determined by substituting the previously mentioned variables into equation (2). The resulting volume of ground water (G) entering the lake was 43,900 acre feet. There were two months in which ground water appeared to be flowing out of Houghton Lake. The month of September, 1971, showed a

TABLE 6.--Houghton Lake Water Levels.*

Date	Reading	ΔS (ft.)	ΔS (Acre/ft.)
Sept. 1, 1971	7.64		
		-.19	- 3,700
Oct. 1, 1971	7.45		
		+.03	+ 590
Nov. 1, 1971	7.48		
		+.20	+ 3,900
Dec. 1, 1971	7.68		
		+.77	+15,000
Jan. 1, 1972	8.45		
		+.37	+ 7,300
Feb. 1, 1972	8.82		
		+.25	+ 4,900
Mar. 1, 1972	9.07		
		+.02	+ 390
Apr. 1, 1972	9.09		
		+.26	+ 5,100
May 1, 1972	9.35		
		-.63	-12,000
June 1, 1972	8.72		
		-.30	- 5,900
July 1, 1972	8.42		
		-.40	- 7,800
Aug. 1, 1972	8.02		
		+.26	+ 5,100
Sept. 1, 1972	8.28		
			+13,000

*U.S.G.S. staff gage located at bridge on old U.S. 27 near outlet of Muskegon River.

ground water loss from the lake of -715 acre-feet. Nothing unusual occurred during the month (Table 7), there was a lowering of lake level of 3,700 acre feet, however this would be expected because evaporation (E) was greater than precipitation (P) and outflow exceeded inflow. The lake level according to the staff gage at the mouth of the Muskegon River (Table 6) had a reading of 7.45 on October 1, 1971, this reading is the lowest recorded for the period from September, 1971, through August, 1972. Therefore, it is likely that the water table in the area during that period was low and that ground water input was minimal, resulting in a net loss of ground water from the lake. This loss probably occurred from lake water moving into the glacial outwash channel on the northeast side of the lake near the outlet of the Muskegon River. July, 1972, also showed a negative value for ground water of -810 acre-feet. It is evident that, as precipitation increases during the winter and spring months, ground-water input is at its highest. During the summer months, when precipitation is low and evaporation high, there is a possibility that ground-water loss from the lake exceeds ground-water flow into the lake system. The water budget cannot actually identify a ground water loss but only implies the same.

The water-budget for Houghton Lake is most reliable when interpreted on an annual basis. Interpretations made on a monthly basis are subject to erronious conclusions

TABLE 7.--Houghton Lake-Water Budget.

		(Acre-Feet)						
		-I		-P	+E	±ΔS	+0	±G.W.
Month	Year	Tributaries Major	Minor*	Prec.	Evap.	Change in Storage	Outflow	Ground Water
Sept.	1971	1,900	655	2,650	4,250	- 3,700	3,940	- 715
Oct.	1971	2,120	245	780	2,310	590	3,140	+ 2,900
Nov.	1971	2,150	984	1,900	1,600	3,900	2,800	+ 3,270
Dec.	1971	4,880	922	4,300	1,490	15,000	6,460	+12,800
Jan.	1972	2,950	245			7,300	4,300	+ 8,405
Feb.	1972	2,880	460			4,900	3,570	+ 5,130
March	1972	4,229	1,780			390	8,850	+ 3,230
April	1972	15,990	3,570	13,300	5,960	5,100	22,020	+ 220
May	1972	11,400	984	3,040	9,260	-12,000	20,290	+ 2,130
June	1972	2,870	714	3,380	6,580	- 5,900	8,330	+ 2,050
July	1972	2,400	676	4,760	8,370	- 7,800	6,460	- 810
Aug.	1972	3,030	533	8,620	5,280	+ 5,100	5,160	+ 3,360
TOTALS		56,800	11,700	43,000	45,100	+13,000	95,300	+41,900
		68,600						

*Discharge of minor tributaries from Oct. thru Aug. based on means of previous year (1970-71).

due to; (1) the fact that April includes the precipitation and evaporation for January through April, (2) events, such as storms and spring floods, cross monthly boundaries, and (3) lack of information on the above items.

Figures 22 and 23 show the relative importance of the components of the hydrologic cycle in the Houghton Lake basin on an annual basis.

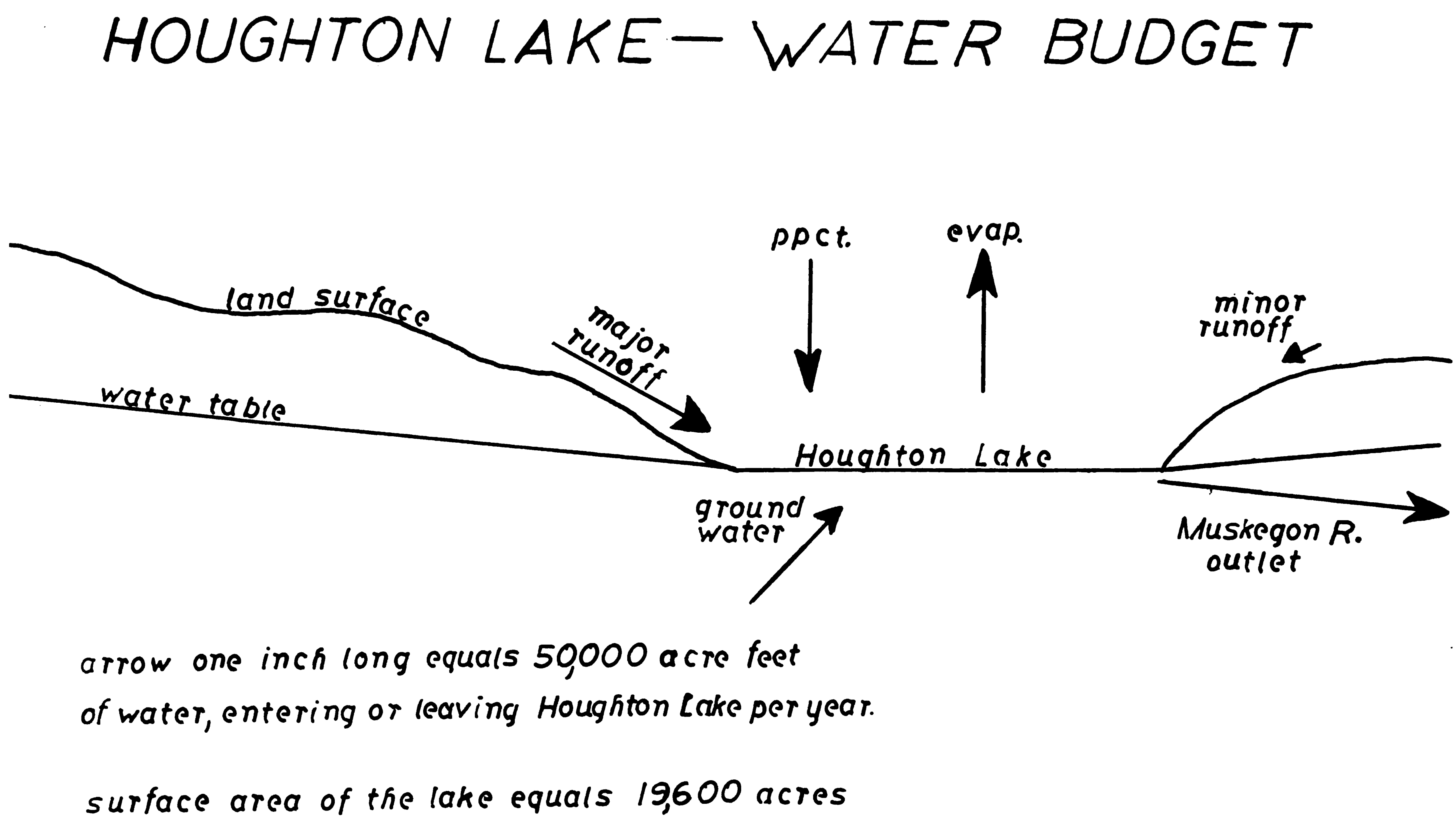


Figure 22.--A diagramatic scheme of the Houghton Lake--Water Budget.

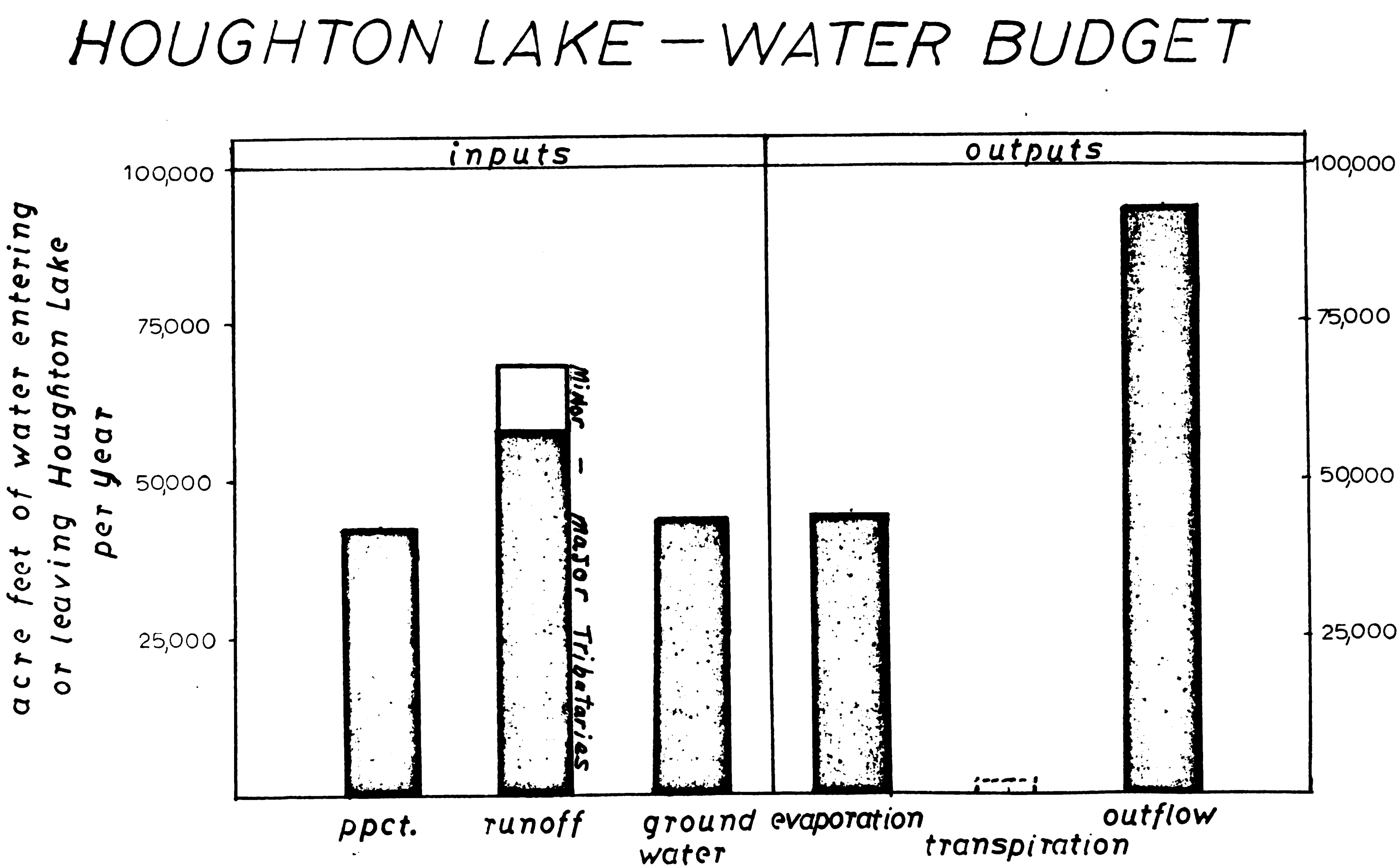


Figure 23.--A graphical representation of the Houghton Lake--Water Budget.

CHAPTER III

FLOW-NET ANALYSIS

Flow-net analysis or simply a flow net and the use of Darcy's Law can be used to determine the volume of ground water entering Houghton Lake. With this method only the volume of ground water moving through the upper twenty feet was calculated. Characterization of the volume of ground water moving through this twenty feet is important because it has the potential of chemical contamination from fertilization and domestic sewage-disposal practices. To understand the significance of ground-water flow through the occupied zone the volumes can be compared to the total volume of ground water entering the lake as calculated in the water-budget of Houghton Lake.

Darcy's Law will be used to make the ground water calculations. The law is expressed as

$$q = Q/A = Kdh/dl \qquad (3)$$

where q equals the rate of discharge, Q equals flow rate, K is the hydraulic conductivity of the soil and sediment, A equals cross-sectional area available for ground-water movement, and dh/dl equals the change in potentiometric slope from the ground-water divides to the discharge area, Houghton Lake. For the problem in this thesis the equation can be restated as

$$Q = AKdh/dl \qquad (4)$$

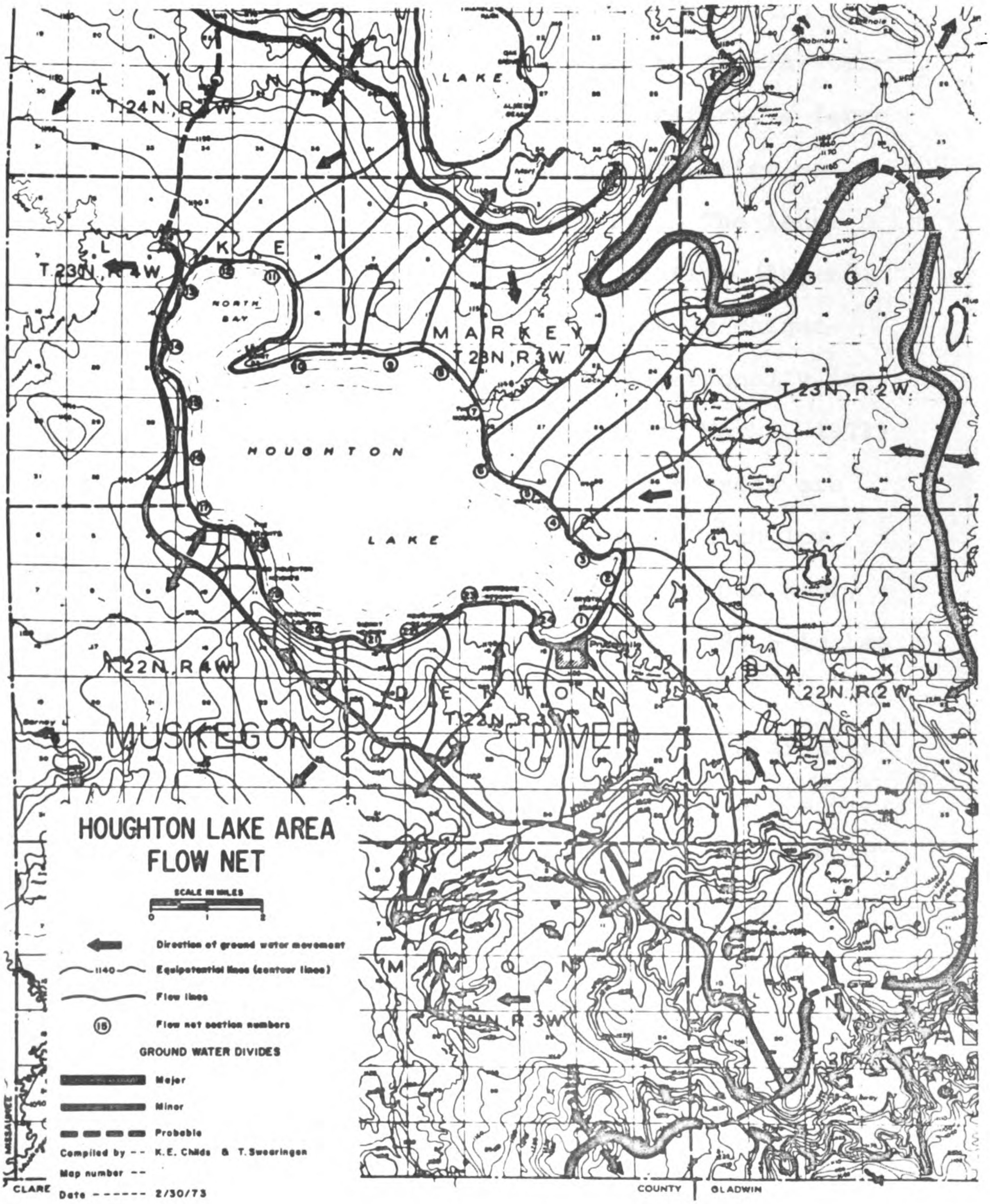
Use of Darcy's Law, requires that methods be established to determine values for area, slope of the water table, and hydraulic conductivity of the soil and sediment. Slope of the potentiometric surface in the Houghton Lake drainage basin was obtained from the construction of the flow net (Figure 21). The cross-sectional area through which the ground water flows was determined from the construction of a fence diagram (Map 2, see Appendix) displaying sediment hydraulic conductivity in cross-section adjacent to the shoreline of Houghton Lake. Hydraulic conductivity of the soils and sediments below the soil zone were determined from published data (Erickson and Schneider, 1972) and interpretations made from the fence diagram.

Methodology

One of the unknown variables of Darcy's equation (4) is the hydraulic gradient or slope dh/dl. Slopes were determined along each streamline on the flow net. The streamlines were usually spaced approximately one mile apart at the lake shore. However, where the flow lines intersected the boundaries of the flow net, the streamlines may have been several miles apart, and had considerable differences in hydraulic gradient. Therefore, a calculation for slope (Appendix Table C) was made for streamlines on each side of a flow-net section (Figure 21) and then the two slopes were averaged to obtain a single slope for the section.

Hydraulic conductivity K of the soil and sediments surrounding Houghton Lake was determined from Erickson and Schneider (1972). The hydraulic conductivity of the parent material, the soil horizon most closely resembling the original sediment deposited in the area, was used to estimate the conductivities of the sediments below the soil zone. There are nine soil types bordering the shoreline of Houghton Lake. These soils have hydraulic conductivities from 0.2 to 86.3 inches per hour. To facilitate the use of these values in Darcy's Equation (4) the soils were grouped into three categories (Appendix Table D). The hydraulic conductivity for each group was determined by the following procedures: (1) determining the percent of total shoreline which each group occupied, (2) determining the percent of shoreline which each soil occupied within its own group, (3) multiplying the percent of shoreline which each soil occupied within its own group, by the hydraulic conductivities of the parent material of each soil member of the group, (4) adding all the calculations derived for each soil type within a group together to obtain a group

Figure 21.--Flow net of the Houghton Lake drainage basin.


HOUGHTON LAKE AREA
FLOW NET
SCALE IN MILES
0 1 2
Direction of ground water movement
1140 Equipotential lines (contour lines)
Flow lines
15 Flow net section numbers
GROUND WATER DIVIDES
Major
Minor
Probable
Compiled by -- K.E. Childs & T. Swearingen
Map number --
Date ------ 2/30/73
T.24N, R.4W
T.23N, R.4W
NORTH BAY
HOUGHTON
LAKE
MARKEY
T.23N, R.3W
T.23N, R.2W
T.22N, R.4W
T.22N, R.3W
T.22N, R.2W
MUSKEGON RIVER BASIN
CLARE
COUNTY
GLADWIN

hydraulic conductivity. Due to the fact that these groups were based on the hydraulic conductivities of soils at the surface and ground water volumes are being calculated for depths to twenty feet, a method was needed to display conductivity changes below the soil zone. Therefore, a fence diagram displaying relative sediment conductivities was constructed for the Houghton Lake shoreline. The fence diagram (Map 2) was constructed from information (Appendix Table E) derived from logs of 81 water wells (Michigan Geological Survey-water well files) and 36 personally installed water wells and borings (Williams and Works, 1971) made in the Houghton Lake area. Two distinct areas are shown on the fence diagram (Map 2); (1) areas with low hydraulic conductivity or less than 1.0 inches per hour, and (2) areas with high conductivity or 1.0 to 83.6 inches per hour.

A cross-section (Map 2) covering the same area as the fence diagram, was also constructed to facilitate a determination for area A. The areas were calculated with the aid of a planimeter for each soil group that occurred within a flow net section (Map 2). These soil groups (Appendix Table B) were based on phosphorus absorption capacities of the soils (Erickson and Schneider, 1972).

Results

The volume of ground water entering Houghton Lake through the upper twenty feet in soil group A (Table 8) was

TABLE 8.--Quantity of Ground Water Entering Houghton Lake Through 20 Feet of Soil Type A.

Flow Net Section#	Area ($ft.^2$)	X Hydraul. Conduct. ft./day	X Slope	= ($ft.^3$/day) Quantity	Total for Section (Soil Type A) ($ft.^3$/day)
1	12,407	172.60	.0027	5,782	
	20,422	41.38		2,282	
	11,089	1.65		49	8,113
2	None				
3	77,895	41.38	.0016	5,157	5,157
4	116,842	41.38	.0013	6,284	6,284
5	50,190	41.38	.0018	3,738	3,738
6	124,471	41.38	.0021	10,816	10,816
7	78,751	41.38	.0032	10,428	
	18,970	1.65	.0032	100	10,528
8	77,736	41.38	.0035	11,259	
	2,947	1.65	.0035	17	11,275
9	None				
10	205,980	41.38	.0024	20,456	
	7,328	1.65	.0024	29	20,485
11	31,058	41.38	.0030	3,856	
	16,723	1.65	.0030	83	3,938
12	69,816	41.38	.0026	7,511	
	81,958	1.65	.0026	352	7,862
13	92,148	41.38	.0019	7,245	
	50,811	1.65	.0019	159	7,404
14	106,656	41.38	.0019	8,358	8,358
15	72,622	41.38	.0013	3,907	
	34,034	1.65	.0013	73	3,979
16	43,346	41.38	.0013	2,332	
	59,443	1.65	.0013	128	2,459
17	16,462	41.38	.0030	2,044	
	101,585	1.65	.0030	503	2,546
18	11,042	41.38	.0038	1,736	
	14,254	1.65	.0038	89	1,825
19	None				
20	24,794	41.38	.0141	14,466	
	99,276	1.65	.0141	2,310	16,775
21	29,737	41.38	.0078	9,598	
	11,041	1.65	.0078	142	9,740
22	105,600	41.38	.0042	18,353	18,353
23	110,418	41.38	.0029	13,250	13,250
24	144,145	41.38	.0022	13,122	13,122
Total all Type A Soil					186,000
Average Quantity of Water per mile (18.0 Miles)					10,330
Average Quantity of Water per mile/2 feet					1,033

calculated as 1,560 acre feet per year, this volume represents the largest amount of ground water entering the lake of the four soil groups. A close second with 1,500 acre feet per year of ground water entering Houghton Lake was soil group B. However, soil group B has a larger volume per mile 319 acre feet per year compared to soil group A with 86 acre feet per year per mile. This occurred because there are only 4.75 miles of soil group B compared to 18 miles of shoreline occupied by soil group A.

The ground water entering Houghton Lake through soil group C is 23 acre feet per year and 6.6 acre feet per mile per year (Table 10). Soil Type D (Table 11) has a ground water input of 9.0 acre-feet per year per mile. Soil groups C and D have considerably lower volumes of ground water input compared to groups A and B because C and D soils are predominantly composed of fine size sediment and have hydraulic conductivities less than 1.65 feet per day.

The total volume of ground water entering Houghton Lake through the upper twenty vertical feet of sediment adjacent to the shoreline of the lake equals approximately 3,100 acre feet per year. Slightly over one-half of the ground water entering Houghton Lake through the occupied zone enters through soil group A. All but 32 acre feet per year of the remaining volume enters the lake through soil group B, therefore, soil type A and B are the major areas of concern.

TABLE 9.--Quantity of Ground Water Houghton Lake Through 20 Vertical Feet of Soil Type B.

Flow Net Section#	Area (ft.^{2})	X	Hydraul. Conduct. ft./day	X	Slope	=	(ft.^{3}/day) Quantity	Total for Section (ft.^{3}/day)
1	60,228		172.60		.0027		28,067	
	67,757		41.38				7,570	35,640
2	38,947		172.60		.0029		19,495	
	69,061		41.38				8,288	27,780
5	13,652		172.60		.0018		4,241	
	43,766		41.38				3,260	7,501
7	4,068		172.60		.0032		2,247	
	4,716		1.65				24.89	2,272
8	31,134		172.60		.0035		18,810	18,810
9	36,763		172.60		.0030		19,036	
	7,003		1.65				34.66	19,070
21	51,696		172.60		.0078		69,600	
	11,042		1.65				142	69,740
	Total Soil Type B							180,800
	Average quantity of water per mile (4.75 miles)							38,060
	Average quantity of water per mile/2'							3,806

TABLE 10.--Quantity of Ground Water Entering Houghton Lake Through 20 Feet of Soil Type C.

Flow Net Section#	Area ($ft.^2$)	X	Hydraul. Conduct. ft./day	X	Slope ft./ft.	=	($ft.^3$/day) Quantity	Total for Section ($ft.^3$/day)
9	60,230		1.65		.0030		298.1	298.1
10	155,600		1.65		.0024		619.1	619.1
11	110,400		1.65		.0030		546.6	546.6
19	75,490		1.65		.0103		1,283.0	1,283.0
	Total for Soil Type C							2,747.0
	Average Quantity of water per mile (3.5 miles)							785.0
	Average Quantity of water per mile/2'							78.4

TABLE 11.--Quantity of Ground Water Entering Houghton Lake Through 20 Feet of Soil Type D.

Flow Net Section#	Area ($ft.^2$)	X	Hydraul. Conduct. ft./day	X	Slope ft./ft.	=	($ft.^3$/day) Quantity	Total for Section ($ft.^3$/day)
18	82,710		1.65		.0038		518.6	518.6
19	32,520		1.65		.0103		552.7	552.7
	Total for Soil Type D							1,071.0
	Average Quantity of water per mile (1.00 miles)							
	Average Quantity of water per mile/2'							

Total value of ground water entering Houghton Lake through all soil groups, to a depth of 20 vertical feet below the water table.

Equals 370,600 $ft.^3$/day

or 3,098 acre ft./yr.

The flow net (Figure 21) indicates that ground water must flow toward Houghton Lake. The potentiometric surface (Appendix Table C) of the ground water in the Houghton Lake basin varies considerably and ranges from 6.66 to 74.25 feet per mile. The slopes are highest along the Houghton Lake moraine on the southeast and are lowest on the west shore and near the Muskegon River Outlet. If lake waters were to move out of the lake via the ground water it would most likely occur along the east side of the lake and near the Muskegon River outlet where a large glacial outwash channel follows the present Muskegon River system.

CHAPTER IV

APPLICATION OF THE WATER BUDGET MODEL

Calculation of Septic-Waste Loading

The model developed in Chapter III, may be applied to calculate nutrient or chemical flux into Houghton Lake. For example, the State of Michigan, Water Resources Commission, Special Projects Unit will use a model, such as is presented in this thesis, to determine phosphorus loading into Houghton Lake via ground water. The Special Projects Unit used the following procedure:

1. They installed shallow, water wells in various soil groups based on phosphorus absorption of the soil, to determine ground-water quality entering the lake.

2. The volume of ground water moving into Houghton Lake through the occupied zone, as developed in the model, was multiplied by the mass of phosphate to determine pounds of phosphorus entering Houghton Lake.

3. Phosphorus entering Houghton Lake due to domestic discharge was determined by establishing what the background ground-water quality was in the area, and subtracting those values from the total phosphorus input. Background values (.005 for phosphorus) were determined by sampling ground water, in isolated areas near Houghton Lake.

Table 12, is a good illustration of how the phosphorus contribution entering Houghton Lake through soil type A, can be determined by using data from the model developed within this thesis.

TABLE 12.--Phosphorus Contribution Entering Houghton Lake Through Soil Type A, an Application of the Ground Water Volumes to Nutrient Loading into Houghton Lake.

Depth Below Water Table	Mean Concent. (ppm)	X Factor (8.345	= Part I Phosphorus lbs/Mill. Gal.	G.W. Discharge Ft.3/day/ mi./2'	X Factor 7.480520 X 10^{-6}	= Part II G.W. Discharge Mill.Gal./ Day/Mile/ 2' Thick	Part I X Part II Phosphorus Load Into Houghton Thru Soil Type lbs./day/mi. 2' Thick
0- 2'	.023	8.345	.1919	1,033.415		.007730	.001483
2- 4'	.006	8.345	.0501	1,033.415		.007730	.000387
4- 6'	.006	8.345	.0501	1,033.415		.007730	.000387
6- 8'	.009	8.345	.0751	1,033.415		.007730	.000581
8-10'	.008	8.345	.0668	1,033.415		.007730	.000516
10-12'	.006	8.345	.0501	1,033.415		.007730	.000387
12-14'	.005	8.345	.0417	1,033.415		.007730	.000322
14-16'	.007	8.345	.0584	1,033.415		.007730	.000451
16-18'	.007	8.345	.0584	1,033.415		.007730	.000451
18-20'	.007	8.345	.0584	1,033.415		.007730	.000451
				TOTAL INPUT (mi./20' thick)			.005416*
Background	.005	8.345	.041	10,334.15	7.48052	.0773	.003169

Total for A = .002569 X mileage 18 miles = .046242 lb./day

(State of Michigan - Special Projects Unit Calculation)

*Average Contribution for Soil A for a Section 1 mile wide and 20' Deep Total .005738 - Background .003169 = .002569 lb./day/mile.

Other Applications

1. Interpretations made from the flow-net and ground-water-input data can be used in the planning and location of waste disposal facilities.

2. The total ground-water-input determined from surface water data, enables an estimate to be made of chemical flux via ground water below the occupied zone.

3. The volumes of all water entering and leaving Houghton Lake could be used to establish sources of high nutrients, and a nutrient budget for the entire lake.

4. The consumptive use of ground and surface waters could be allocated on the basis of a rational estimate of availability and resupply potential.

CHAPTER V

CONCLUSIONS

Houghton Lake is only partially maintained by inflowing ground water. The majority of the water entering the lake enters via the major and minor tributaries. Ground water contributes approximately 38 percent of the total ground and surface water entering the lake. The total volume of ground water entering the lake is 41,900 acre feet, of which 3,100 acre feet or 7.3 percent moves through the upper twenty feet in the occupied shore area.

To best exemplify the significance of the volume of ground-water input to the lake, nutrient loading to the lake based on the above volumes can be used. The volume of ground water moving into Houghton Lake through the occupied zone, transports into the lake approximately 115 pounds of phosphate per year less background. The majority of the ground water moving into Houghton Lake below the occupied zone transports a minimum of approximately 75 pounds of phosphate into the lake system, as calculated from background values.

In summary, only minor volumes of ground water enter Houghton Lake through the upper twenty feet of sediment. Ground water in the Houghton Lake drainage basin, therefore, moves in a downward pattern in the recharge areas and then up into the discharge area (Houghton Lake). Consequently, most of the ground water moves under the occupied area. Further, if all of the ground water had moved horizontally into the lake through the occupied zone, nutrient loading to the lake might be as much as ten times greater than the present load rate.

The volume of ground water entering Houghton Lake is less than the volume of surface water flow into the lake, this is probably due to the fact that Houghton Lake is shallow and only receives ground water from relatively shallow depths compared to other deeper lakes, and to the fact that there are several important tributaries to the large lake which discharge large volumes of surface water. Whether Houghton Lake or any lake receives the majority of its water from ground or surface waters, the volume of ground water that passes through the occupied zone is the water that is significant and has the potential of chemical contamination of Michigan's inland lakes.

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REFERENCES CITED

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APPENDIX

APPENDIX TABLE A.--List of Drains and Tributaries Established by Department of Natural Resources, Water Resources Committee, Inland Lakes Study Unit, State of Michigan.

Drains	Location
2a	North of Silver Drive
12	Chippewa Trail
17	Balsam Street
20	Jefferson Street
21	Elmwood Drive
22	Cedarwood Street
23	Bert Lane
26	Dickerson's Hotel
26a	Rock Shop
27	Maple Street
28	Elm St. to Gr. Rapids St.
29	Lake Road
33	Flora Avenue
34	Co. Rd. 270, Ditch
35	Peter Avenue
43	West Side of Camp Grd.
44	Middle of Camp Grd.
44a	East of Camp Grd.
47	Ditch Zone 30
48	McDonald Landing
51a	Ina Street
53	Townline Landing
54	West Lake Road
55	East of West Lake Rd.
56	Flint Road
57	Spring Creek Landing
59	Oneida Drive
60	Public Access Site (east shore)
Minor Tributaries	
T-2	Sucker Creek
T-16	8th Street Creek
T-6	Unnamed Creek at Cherokee
C-2	Canals on Iroquois
Major Tributaries--Inflowing	
1207.8	Knappen Creek
1207.4	Denton Creek
1206.9	Spring Brook Creek
1205.5	The Cut
Major Tributaries--Outflowing	
1209.	Muskegon River

APPENDIX TABLE B.--Soil Groups for Which Ground Water Volumes were Calculated.

Houghton Lake Shoreline Soil Groupings*					
Soil Group	Symbol	Soil Name	Shoreline Mileage	% of Total Shoreline Mi.	Total Miles For Group
A	NS	Newton Loamy Sand	12.25	45.00	
	RP	Rifle Peat	3.25	11.93	
	SS	Saugatuck Sand	2.25	8.30	
	H	Houghton Muck	.25	.90	18.00
B	RS	Rubicon Sand	3.00	11.00	
	GGS	Grayling Sand	1.50	5.50	
	RNS	Roselawn Sand	.25	.90	4.75
C	BL	Bergland Loam	3.50	12.90	3.50
D	NRL	Nester Loam	1.00	3.70	1.00

*A ground water input was determined for each of the groups listed.

APPENDIX TABLE C.--Slope Computation for Ground Water in the Houghton Lake Drainage Basin.*

Section Number	dh/dl	Dist./ mile	Slope Ft./mile	dh/dl	Dist./ mile	Slope Ft./mile	Avg.	Slope Ft./mile	Slope Ft./ft.
1	1175/1138	3.75	9.86	1260/1138	6.50	18.76	14.32	14.32	.0027
2	1260/1138	6.50	18.76	1220/1138	6.75	12.14	15.46	15.46	.0029
3	1220/1138	6.75	12.14	1170/1138	7.00	4.57	8.36	8.36	.0016
4	1170/1138	7.00	4.57	1130/1138	4.50	9.33	6.95	6.95	.0013
5				1180/1138	4.50	9.33	9.33	9.33	.0018
6	1180/1138	4.50	9.33	1180/1138	3.25	12.92	11.13	11.13	.0021
7				1180/1138	2.50	16.80	16.80	16.80	.0032
8				1180/1138	2.25	18.66	18.66	18.66	.0035
9				1185/1138	3.00	15.66	15.66	15.66	.0030
10	1185/1138	3.00	15.66	1185/1138	5.00	9.40	12.53	12.53	.0024
11				1185/1138	3.00	15.66	15.66	15.66	.0030
12	1190/1138	4.00	13.00	1190/1138	3.50	14.85	13.93	13.92	.0026
13				1140/1138	.20	10.00	10.00	10.00	.0019
14				1140/1138	.20	10.00	10.00	10.00	.0019
15				1140/1138	.30	6.66	6.66	6.66	.0013
16				1140/1138	.30	6.66	6.67	6.66	.0013
17				1150/1138	.75	16.00	16.00	16.00	.0030
18				1150/1138	.60	20.00	20.00	20.00	.0038
19	1150/1138	.75	16.00	1175/1138	.40	92.50	54.25	54.25	.0103
20	1175/1138	.40	92.50	1180/1138	.75	56.00	74.25	74.25	.0141
21	1180/1138	.75	56.00	1175/1138	1.40	26.43	41.21	41.21	.0078
22	1175/1138	1.40	26.43	1180/1138	2.40	17.50	21.96	21.96	.0042
23	1180/1138	2.40	17.50	1180/1138	3.25	12.92	15.21	15.21	.0029
24	1180/1138	3.25	12.92	1175/1138	3.75	9.87	11.39	11.39	.0022

*Determined from flow net map no. 1.

APPENDIX TABLE D.--Hydraulic Conductivity Groups for Soils in the Houghton Lake Area.

Group	Soil Type	Percent of Total Shoreline Mi.	Percentage of Group	Hydraul. Cond. of Parent Mat. Inches Per Hr.	Group Conductivity	
					In./Hr.	Ft./Day
Low	Nester loam	3.7	.22	.2		
	Bergland loam	12.9	.78	1.0		
	Total	16.6	100.		.824	1.65
Med.	Newton loamy Sd.	45.0	.63	22.7		
	Saugatuck sand	8.3	.11	8.1 (S_2 Horizon)		
	Grayling sand	5.5	.07	18.1		
	Rifle peat	11.95	.16	22.7		
	Houghton muck	.9	.01	22.7		
	Total	71.63	98.00		20.69	41.38
High	Rubicon sand	11.00	.92	86.3		
	Roselawn sand	11.00	.08	86.3		
	Total	11.9	100.00		86.3	172.6

APPENDIX TABLE E.--Selected Well Logs in the Houghton Lake Area for the 1973 Fence Diagram.

	Hydraulic Low	Conductivity High
1. (22N-4W-3), located at the end of Barkman Ave. Houghton Heights, installed by special projects unit and designated DL-05-01, Soil: Nester loam.	2-20'	0-2'
2. (22N-4W-2), Well St. off M55 Roscommon TWP., Owner: Floyd Engel. Well log on File Geological Survey.	10-20'	
3. (22N-4W-2), Clarence St. Roscommon TWP., Owner: Carl Watters. Well log on File Geological Survey.	5-20'	0-5'
4. Boring taken by Williams and Works, under contract for Sewage Systems at Houghton Lake. Boring #10.	5.5'-17.5'	0-7.5'
5. (22N-4W-11), located 800 Lakewood Drive, installed by special projects unit and identified as CM-13-01. Soil: Bergland loam.	4-20'	0-4'
6. Boring taken by Williams and Works, taken under contract for Sewage System at Houghton Lake. Identified as B 16.	2-12.5'	0.2'
7. (22N-4W-11), located at end of McKinley St. installed by special projects unit, and designed DH-01-02.	4-12'	0-4'
8. (22N-4W-13), 388' east of Madelin St., installed by Special Projects unit and identified as AM-75-01. Soil type: Newton loamy sand.	4-14'	0-4'
9. Boring taken by William and Works under contract for Sewage System, Houghton Lake, designated as B 29.	12-17.5'	0-12'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
10. (22N-13W-18), 338' east of Roscommon Ave., driven by Special Projects unit and identified as BM-12-01. Soil type: Rubicon sand.		0-20'
11. (22N-3W-18-5), on file- well logs, Geological Survey.		0-20'
12. (22N-3@-17), located at end of Visnaw Ave., installed by special projects unit and identified as AH-72-01. Soil type: Newton loamy sand.		0-20'
13. (22N-3W-17), located at end of Beverly St., driven by Special Project unit and identified as AH-70-01. Soil type: Newton Loamy sand.		0-20'
14. (22N-3W-7-22), on file- Well logs at Geological Survey.		0-20'
15. (22N-3W-9-3), on file- Well logs at Geological Survey.		0-20'
16. (22N-3W-9-5), on file Geological Survey, Well log section. Denton TWP.		0-20'
17. (22N-3W-9-5), on file Geological Survey, Well log section. Denton TWP.		0-20'
18. (22N-3W-15) Tamarack St., Denton twp., Owner Lloyd Lee. On file Well logs Geological Survey.		0-20'
19. (22N-3W-15), located 137' west of Spruce Ave., friven by Special projects unit and identified as BH-10-02. Soil type: Grayling sand.		0-20'
20. (22N-3W-15) same as above except designated BH-10-01.		0-20'
21. (22N-3W-15) 5th Avenue. Denton TWP., 3 blocks from M18 Owner: Richard Koblen.		0-20'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
22. (22N-3W-15), located at end of 2nd street, driven by special projects unit and identified as BH-09-01. Soil type: Grayling sand.		0-20'
23. (22N-3W-18) 300 yards north of M55 and M18, Denton TWP Owner: D.K. Sugar. Well log on file Geological Survey.		0-20'
24. (22N-3W-14), 50' east of Bay St. in Prudenville, driven by special projects section and identified as AH-61-01.	13-20'	0-13'
25. (22N-3W-14), Arrowhead Dr., Prudenville, Denton TWP. Owner: Terry Widdis. Log on file Geological Survey.		0-21'
26. (22N-3W-11), located 200' east of Riviera Resort, located corner of M18 and M55, driven by special projects unit and identified as BM-07-01.		0-20'
27. (22N-3W-11), Sunny Brook Estates. Denton TWP., Owner: Otto Schultz. Log on file Geological Survey.		0-21'
28. (22N-3W-11), located 251' north of Matt Ave. driven by special projects unit and identified as BM-05-01. Soil type: Rubican sand.		0-20'
29. (22N-3W, 2-12) log on file Geological Survey.		0-20'
30. (22N-3W-2-14) log on file Geological Survey.		0-20'
31. (22N-3W-2-10) log on file Geological Survey.		0-20'
32. (23-3W-34-1) log on file Geological Survey.		0-20'
33. (22N-3W-34-22) log on file Geological Survey.		0-20'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
34. (22N-3W-34), 15' east of Apacha St., driven by special projects unit and identified as AL-50-01. Soil Type: Newton loamy sand.		0-20'
35. (23N-3W-34-3) log on file Geological Survey.		0-20'
36. (23N-3W-28) Hammond St., 1 block south from McDonald St. Markey TWP. Owner: Ed Belill. Log on file Geological Survey.		0-21'
37. (23N-3W-28-2) log on file Geological Survey.		0-20'
38. (22N-3W-18) end of Timbers Dr. Driven by special projects unit and identified as AM-47-01. Soil type: Newton loamy sand.		0-20'
39. (23N-3W-33) 1/4 mile west of Co. Rd. 100, 3 1/4 miles N. of M55, Markey TWP. Owner: George Simons. Log on file Geological Survey.		0-20'
40. (22N-3W-28), 20' N. of Dale Rd. near Roscommon Co. Airport. Driven by special projects unit and identified as AM-46-01.	4-6'	0-4'-6-20'
41. (23-3W-28), 90' west of Breezy lane, 100' S. of Timber Dr. Markey TWP. Owner: Robert Hause.	10-20'	0-10'
42. (23N-3W-3403) log on file Geological Survey.	14-16'	0-14'-16-20
43. (23N-3W-21-1) log on file Geological Survey.		0-20'
44. (23N-3W-20) Lot #3, 450' S. of Co. Rd. 300 and 1/2 mile east of Flint Rd., Markey TWP., Owner: Harold Beny.		0-20'
45. (23N-3W-20), 360' E. of Flint Rd. driven by special projects and identified as BL-15-01.		0-20'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
46. (23N-3W-20), 388' W. of N. Shore ldg., driven by special projects unit and identified as BL-14-01. Soil type: Rubicon sand.	16-20'	0-16'
47. (23N-3W-20), 1200' east St. James Ch., driven by special projects unit and identified as BL-13-01. Soil type: Rubicon sand.	8-16'	0-8'
48. (23N-3W-19), 1 1/2 mile E. of Co. Rd. 300 and long Pt. Dr., Markey TWP. Owner: John Snuverink.		0-20'
49. (23N-3W-19-1), log on file Geological Survey.	7-14'	0-7'-14-20'
50. (23N-3W-19) log on file Geological Survey.		0-20'
51. (23N-3W-19-6) log on file Geological Survey.		0-20'
52. Boring made by Williams and Works as part of contract for Waste disposal system. B146.		0-20'
53. Same as above. B164		0-20'
54. (23N-4W-24) located 1,084' W. of Byers lane, driven by special projects unit and identified as CL-05-01. Soil type: Bergland loam.		0-20'
55. (23-4W-24) Int. Co. Rd. 300 and Long Point Dr., Lake TWP. Owner: Don Jackson.	15-20'	0-15'
56. Boring made by Williams and Works as part of a contract for waste disposal system. Designated as B141.		0-20'
57. Same as above. Designated as B166		0-20'
58. Same as above. Designated as B167		0-20'
59. Same as above. Designated as B150		0-20'
60. Same as above. Designated as B168		0-20'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
61. (23N-4W-13) located 960' N. of N. Bay ldg., driven by special projects unit. Identified as CL-18-01. Soil: Bergland loam.	10-16'	0-10'
62. Boring made by Williams and Works as part of contract for Sewage Treatment System. B136	9-20'	0-9'
63. Same as above B66.	14-17.5'	0-14'
64. Same as above B62.	6-20'	0-6'
65. Same as above B59.	7-12.5'	0-7'
66. Same as above B129.	3.5-20'	0-3.5'
67. Same as above B33.	7-20'	0-7'
68. Same as above B34.	4-17'	0-4'-17-20'
69. Same as above B127.		0-10'
70. (23N-4W-16) 262' N. of Water St. Driven the summer of 1972 by special projects unit and identified as AL-18-01. Soil type: Newton loamy sand.	6-10'	0-6'-10-20'
71. Boring made by Williams and Works as part of contract for Sewage Treatment System. Designated B124.		0-12.5'
72. Same as above. Designated B36.		0-20'
73. (23N-4W-21) off old 27, 1/4 mile on Bay St., Lake TWP. Owner: William Goodwin. Log on file Geological Survey.		0-20'
74. Boring made by Williams and Works as part of contract for Sewage Treatment System. B123		0-20'
75. (23N-4W-21) W. Hl. Dr., 1 mile N. of U.S. 27, Lake TWP. Owner: Fred Groatt. Log on file Geological Survey.		0-20'

APPENDIX TABLE E.--Continued.

	Hydraulic Low	Conductivity High
76. Boring made by Williams and Works as part of contract for Sewage Treatment System. Designated as B19.	9-12.5'	0-9'
77. Same as above. Designated as B18.	10-12.5'	0-10'
78. Same as above. Designated as B17.		0-12.5'
79. (23N-4W-34) Lake TWP. Owner: Joseph Yurgin. Log on file Geological Survey.	10-20'	0-10'
80. Boring made by Williams and Works as part of contract for Sewage Treatment System. Designated as B34.	4-17'	0-4'-17-20'
81. (23N-3W-34) 300' N. of Holiday Inn on old 27. Driven by special projects unit and identified as AL-05-01. Soil type: Newton loamy sand.	4-14'	0-4'

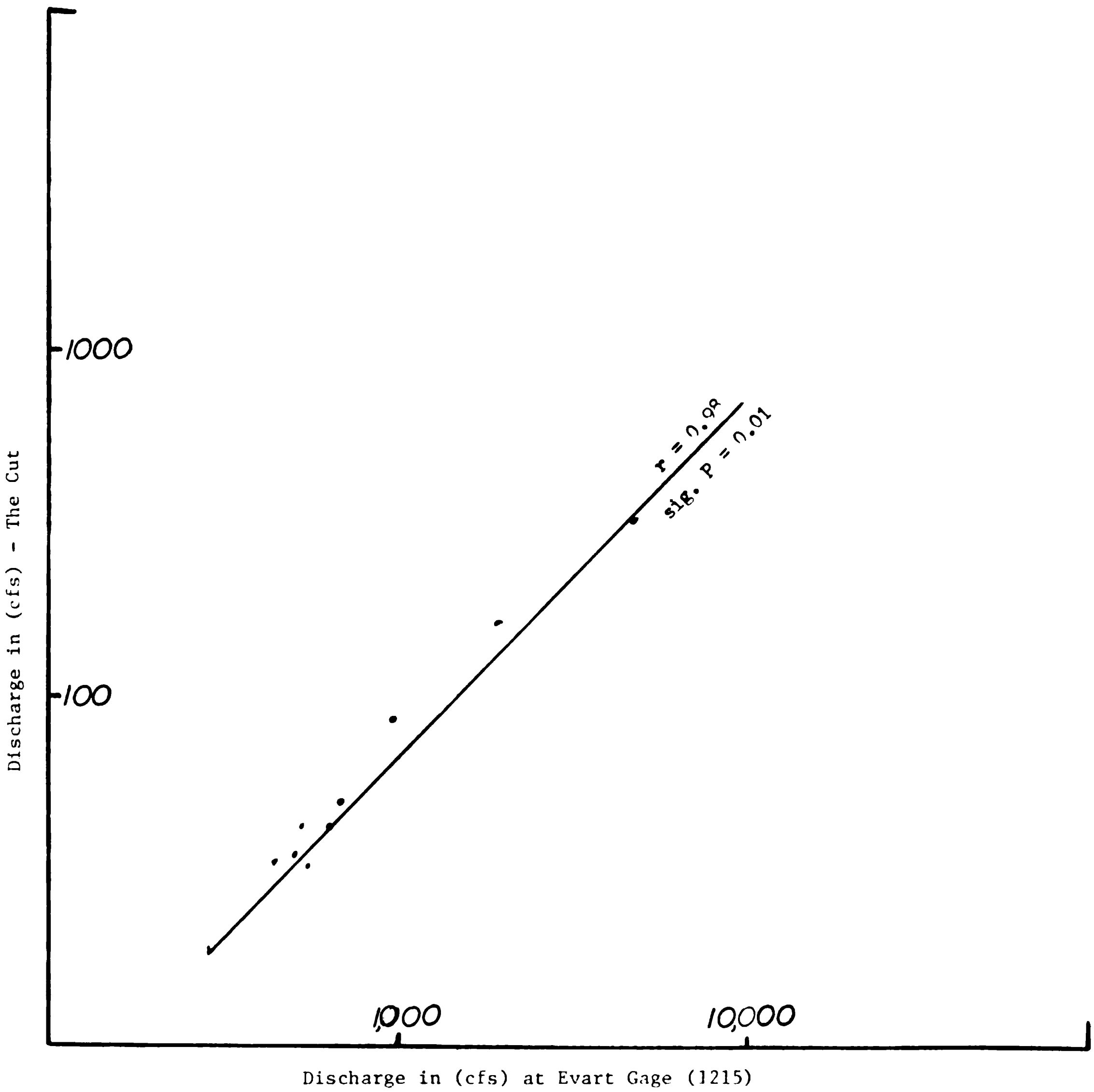


Figure 2.--Discharge correlation for The Cut versus the gage on the Muskegon River at Evart. Data were fit by simple linear regression, where r is the linear correlation coefficient which is significant at P = 0.01. Data points represent biweekly measurements taken at the outlet of The Cut.

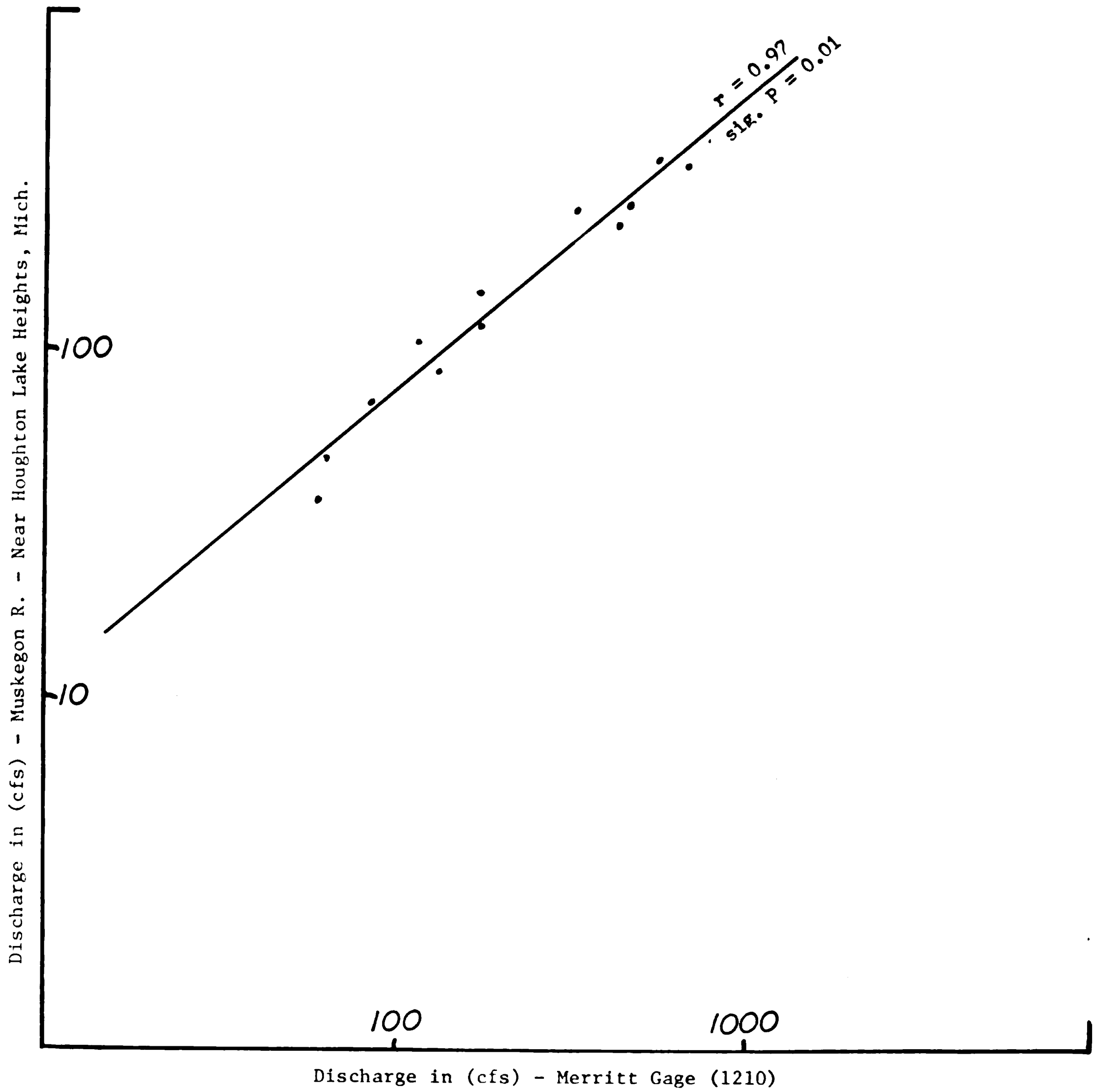


Figure 3.--Discharge correlation for the gage near Houghton Lake Heights, Michigan versus the gage on the Muskegon River at Merritt Gage. Data were fit by simple linear regression, where r is the linear correlation coefficient which is significant at P = 0.01. Data points represent biweekly measurements taken at the outlet of The Cut.

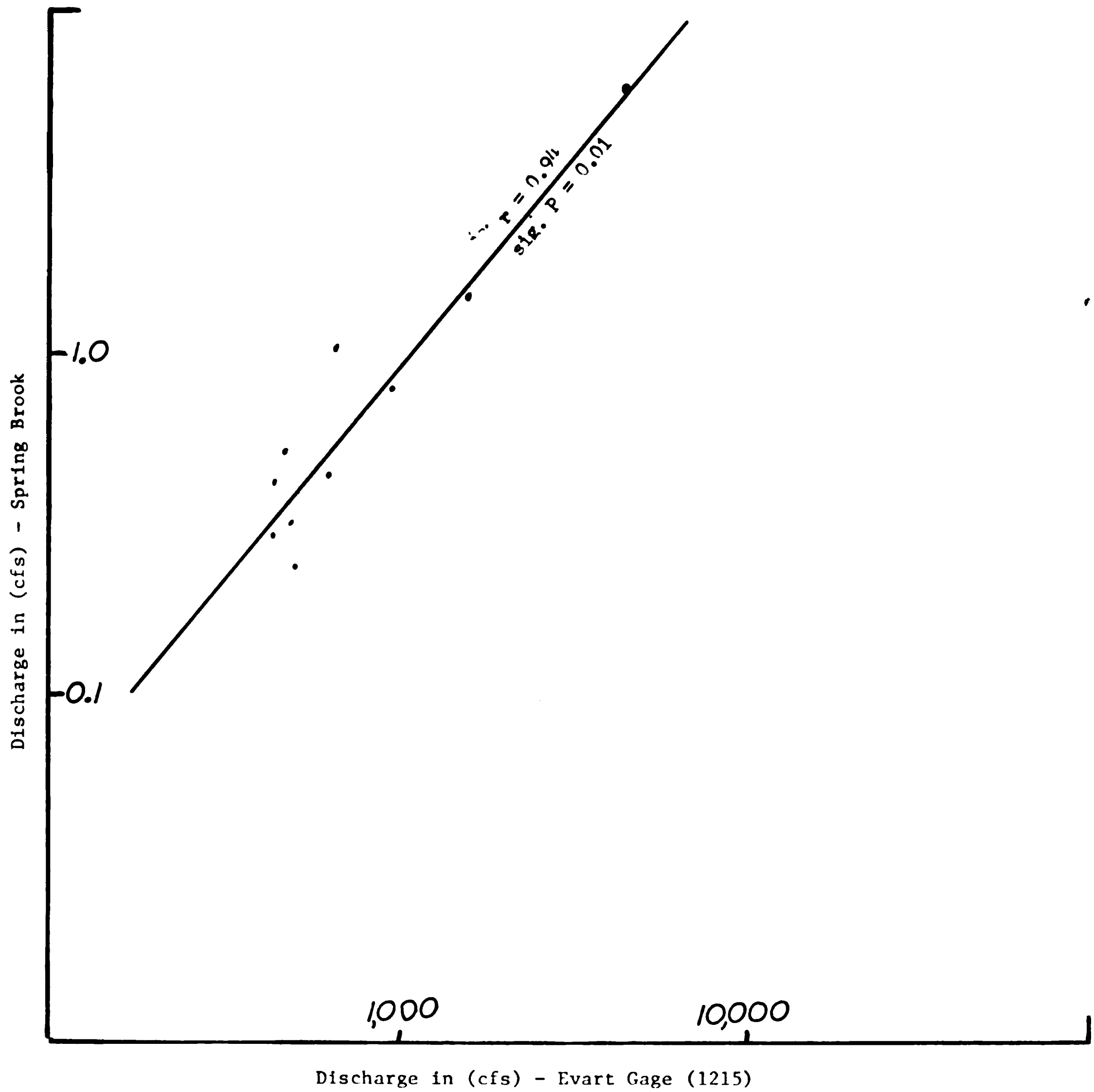


Figure 4.--Discharge correlation for Spring Brook versus the gage on the Muskegon River at Evart. Data were fit by simple linear regression, where r is the linear correlation coefficient which is significant at P = 0.01. Data points represent biweekly measurements taken at the outlet of The Cut.

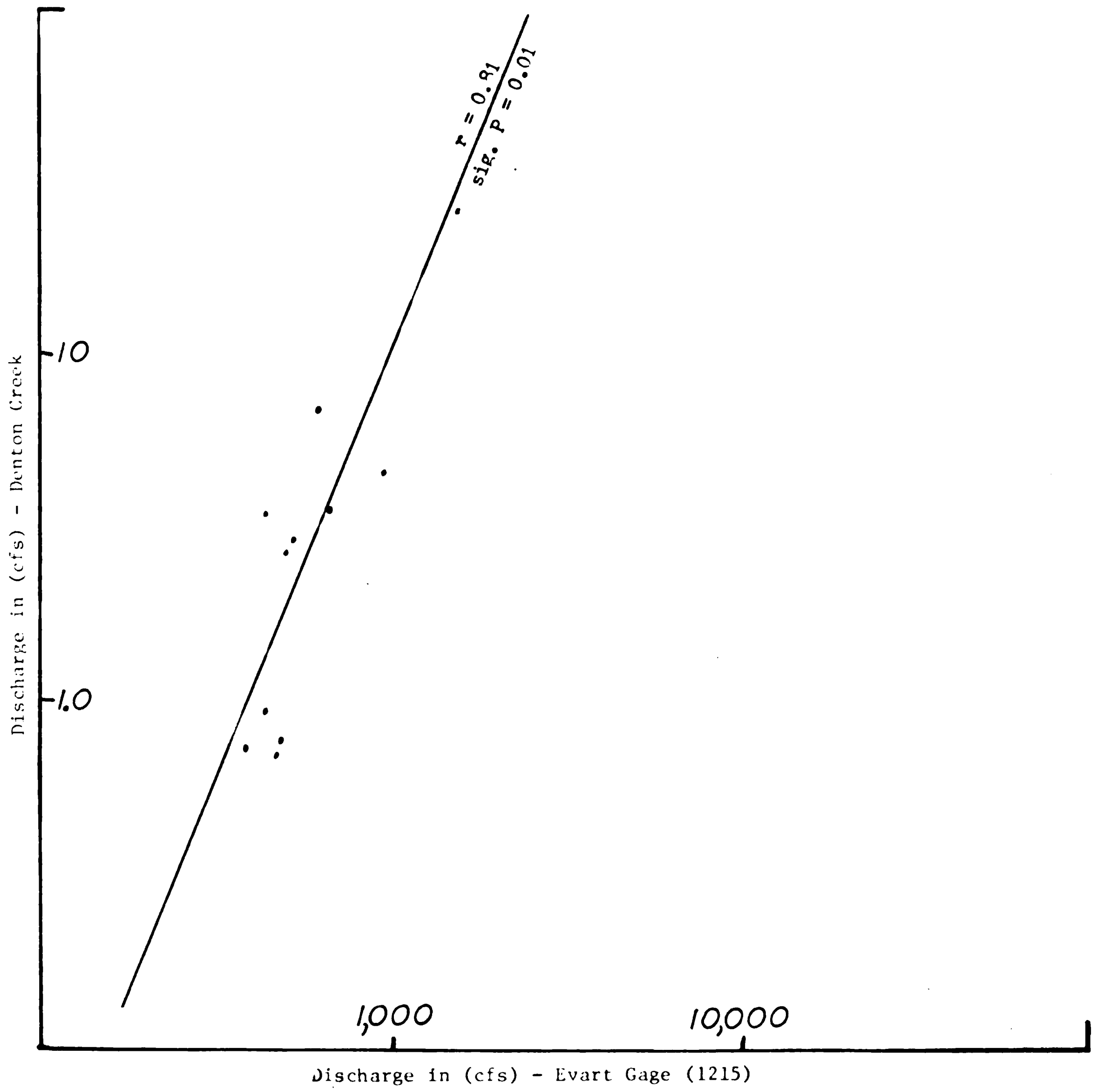


Figure 5.--Discharge correlation for Denton Creek versus the gage on the Muskegon River at Evart. Data were fit by simple linear regression, where r is the linear correlation coefficient which is significant at P = 0.01. Data points represent biweekly measurements taken at the outlet of The Cut.

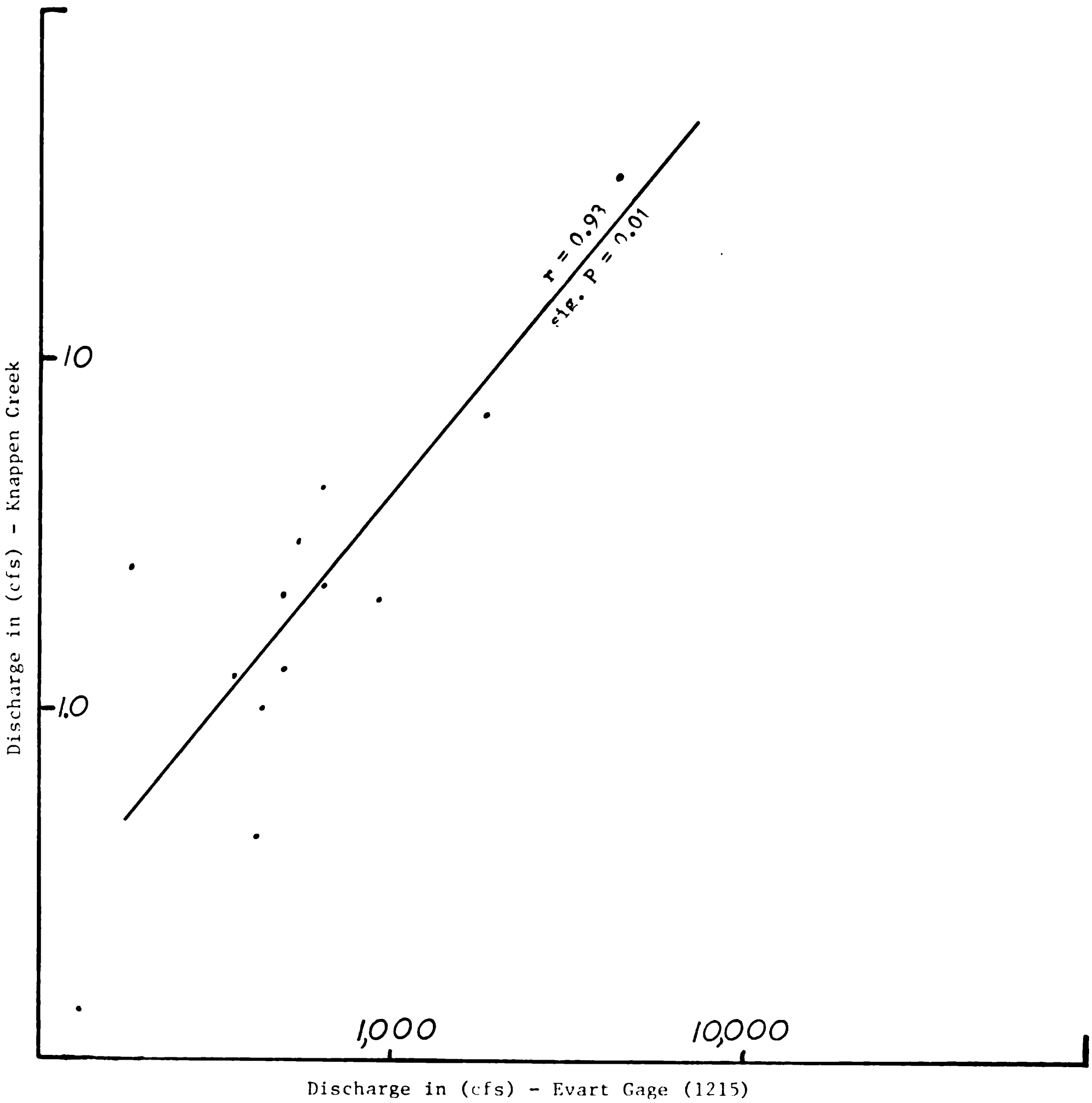


Figure 6.--Discharge correlation for Knappen Creek versus the gage on the Muskegon River at Evart. Data were fit by simple linear regression, where r is the linear correlation coefficient which is significant at P = 0.01. Data points represent biweekly measurements taken at the outlet of The Cut.

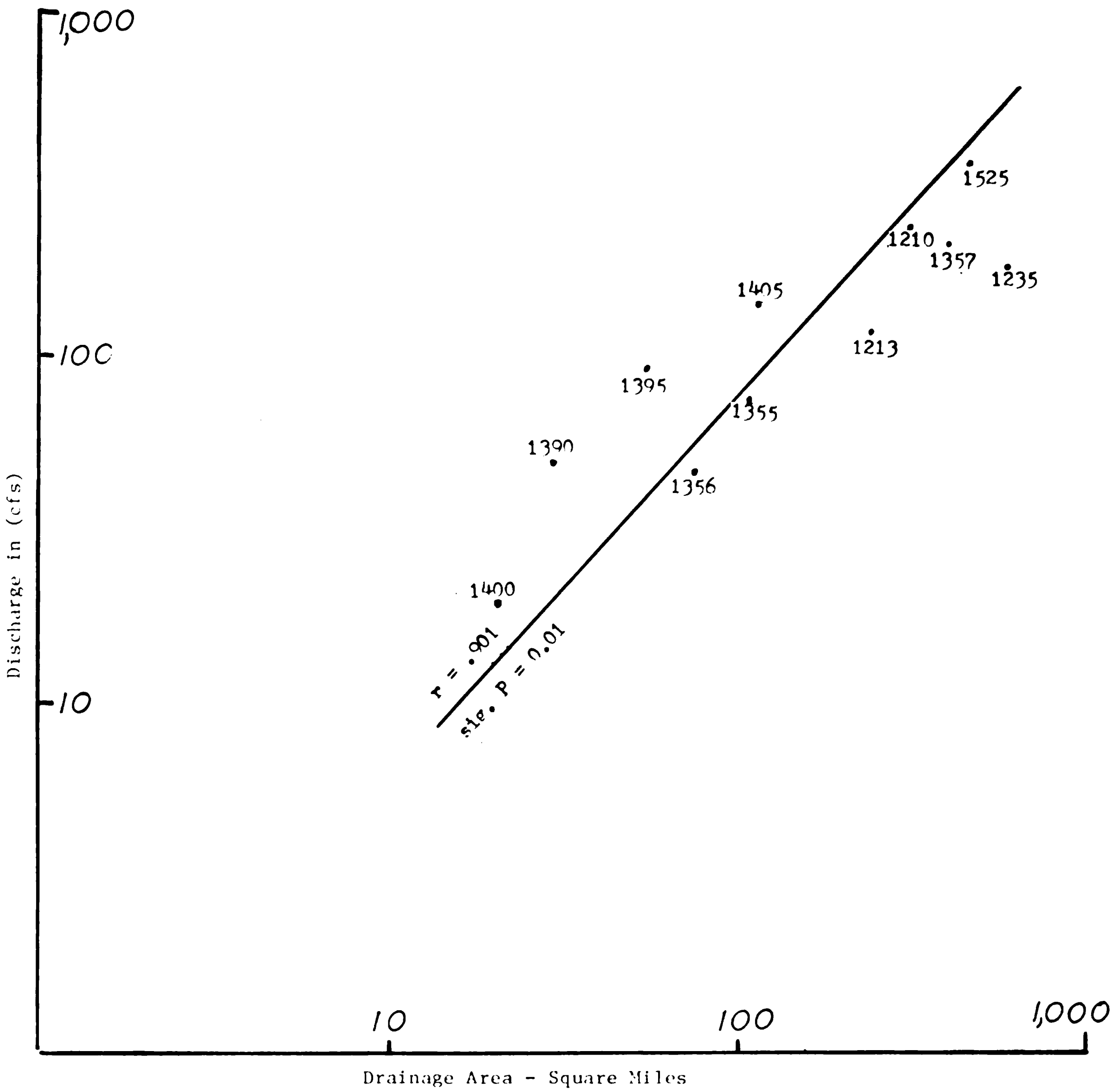


Figure 8.--Drainage Area--Discharge correlation for the period October, 1970, to September, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

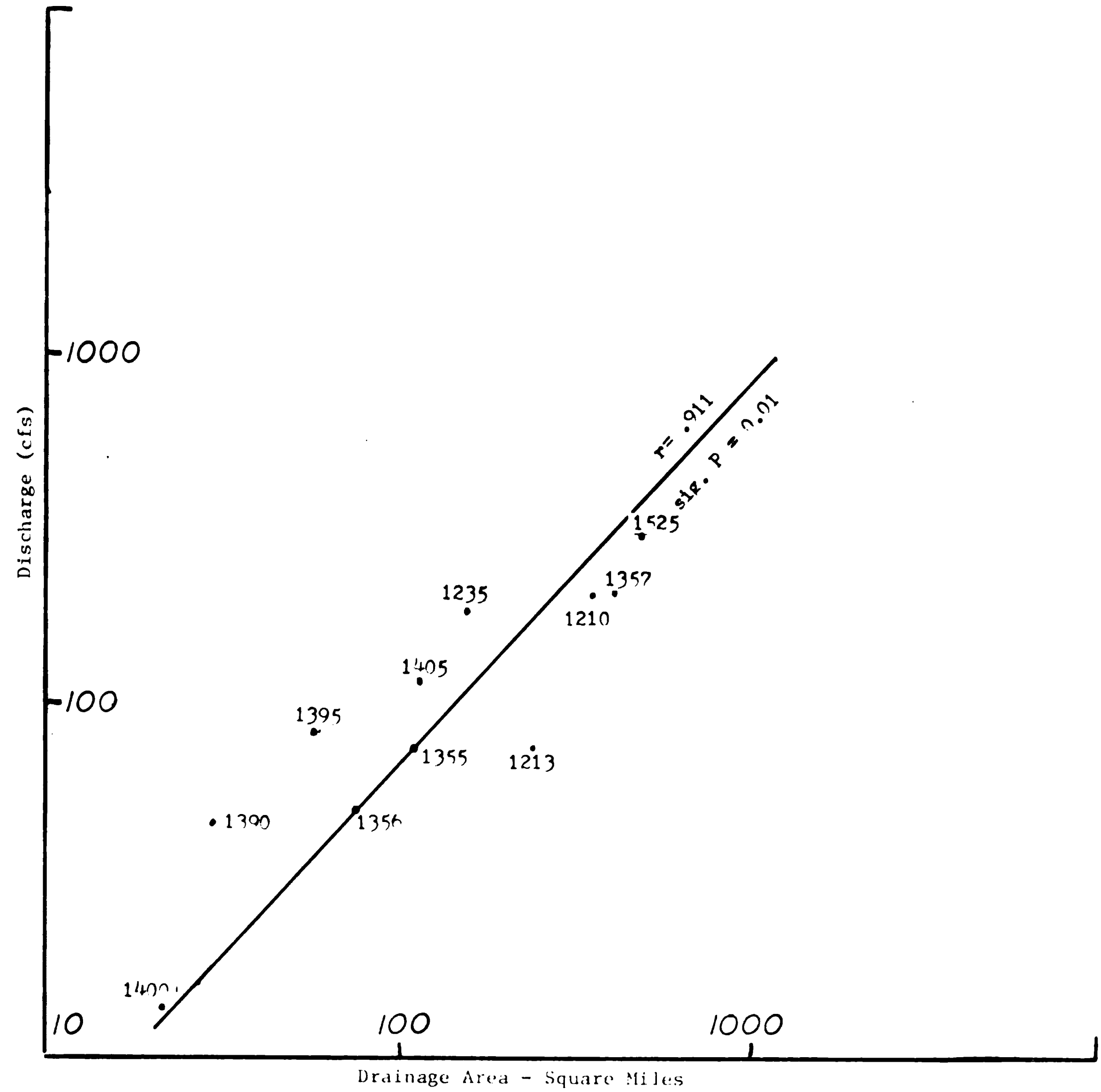


Figure 9.--Drainage Area--Discharge correlation for October, 1970. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

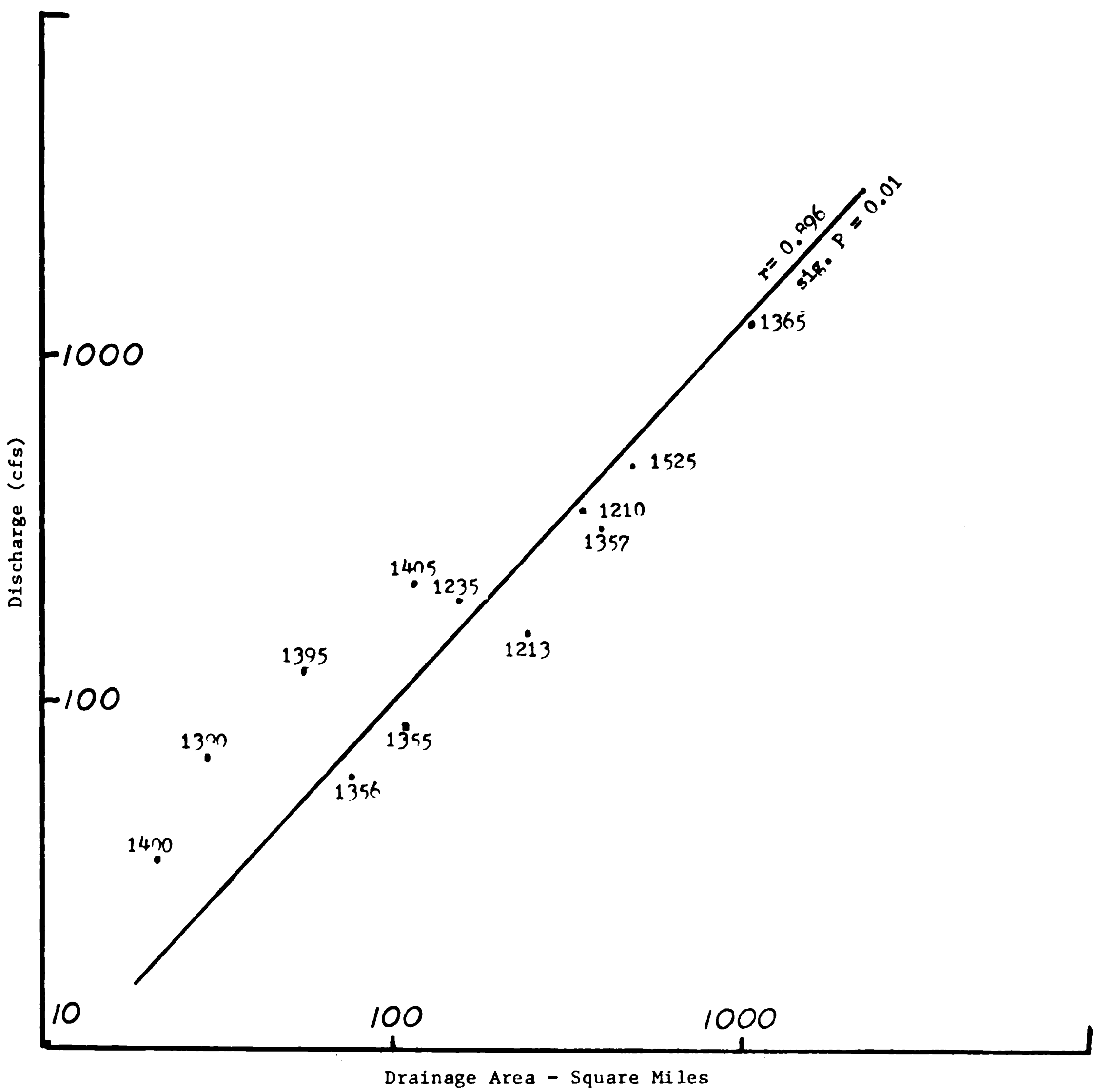


Figure 10.--Drainage Area--Discharge correlation for November, 1970. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

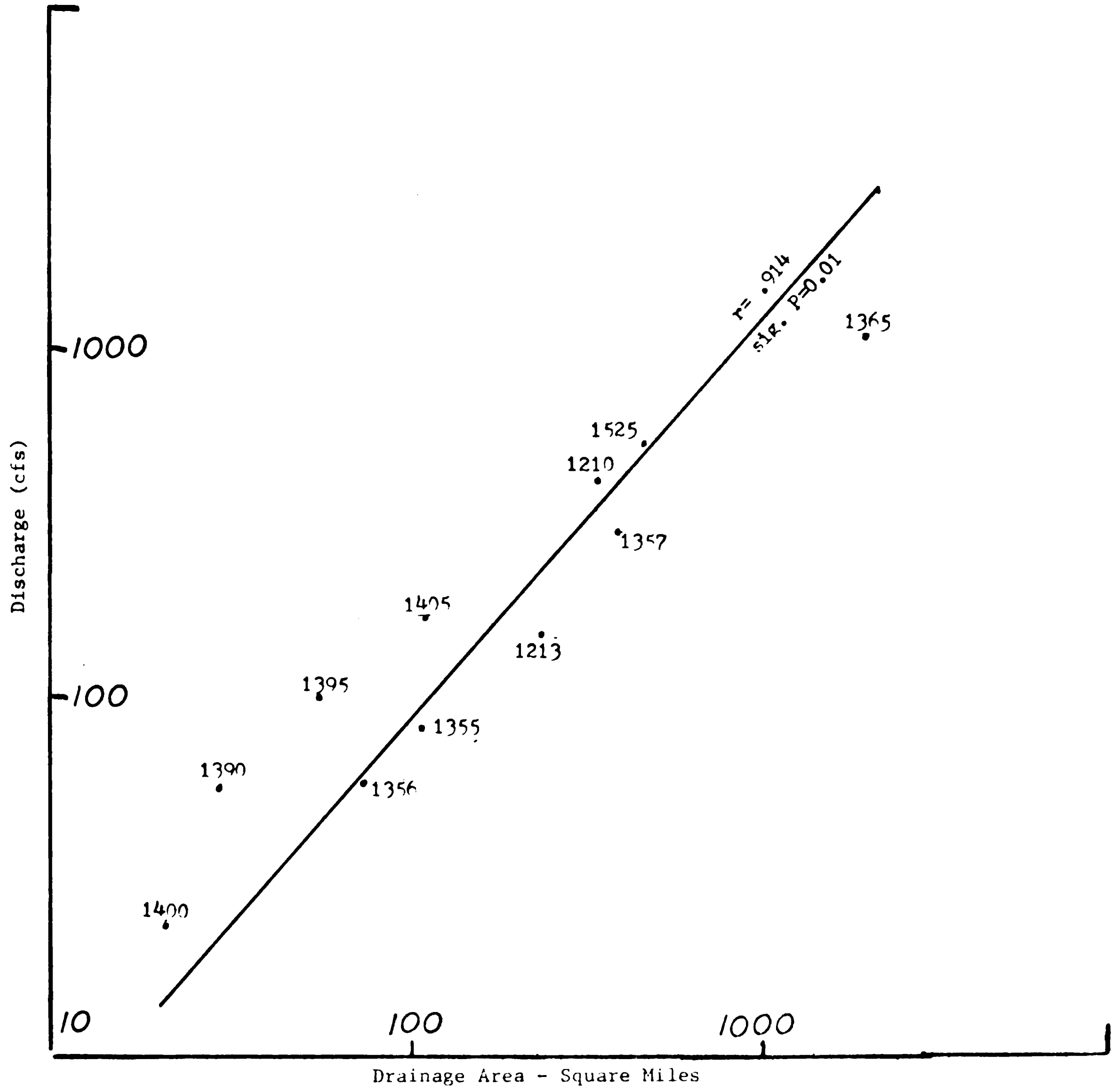


Figure 11.--Drainage Area--Discharge correlation for December, 1970. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

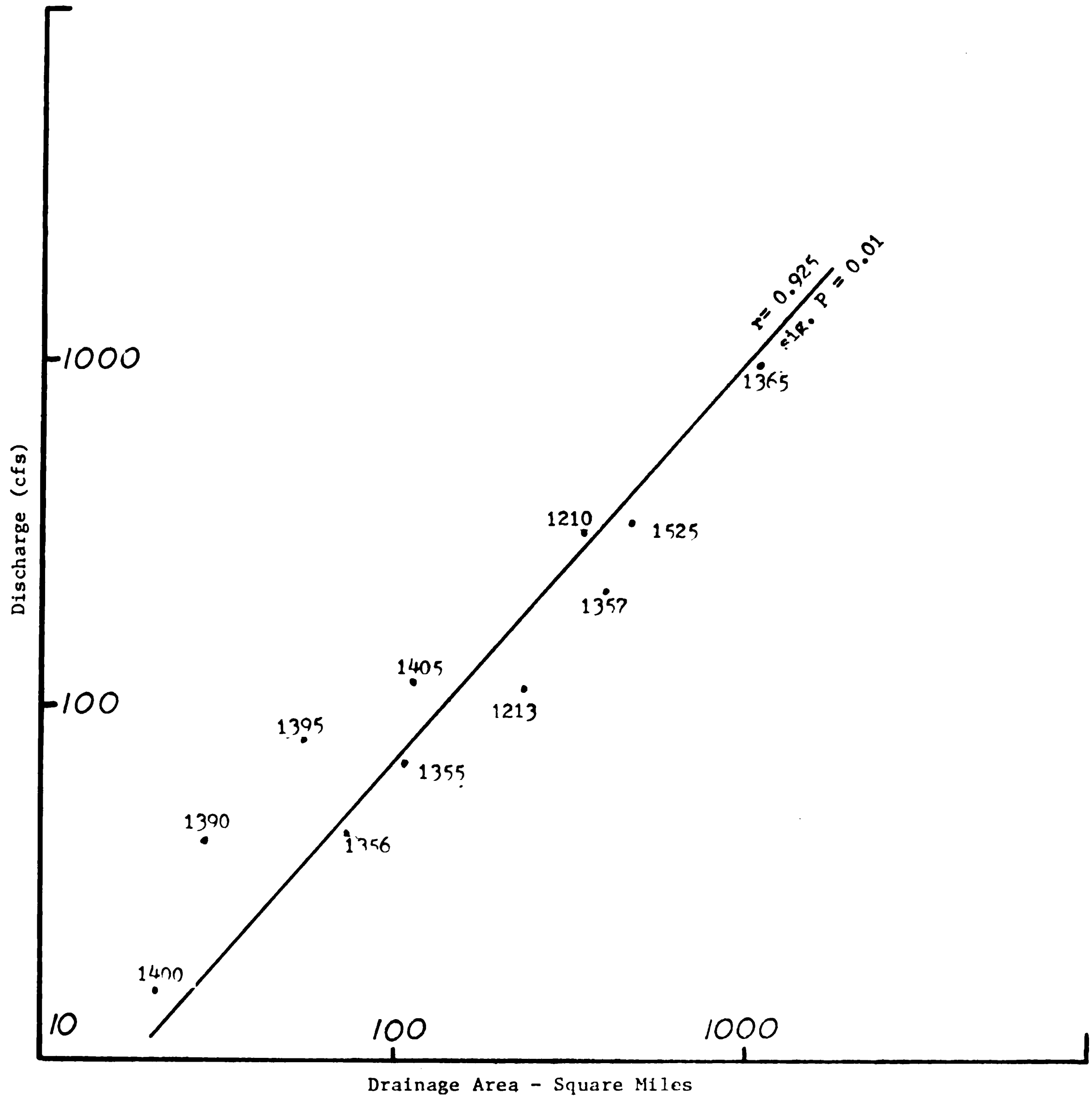


Figure 12.--Drainage Area--Discharge correlation for January, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

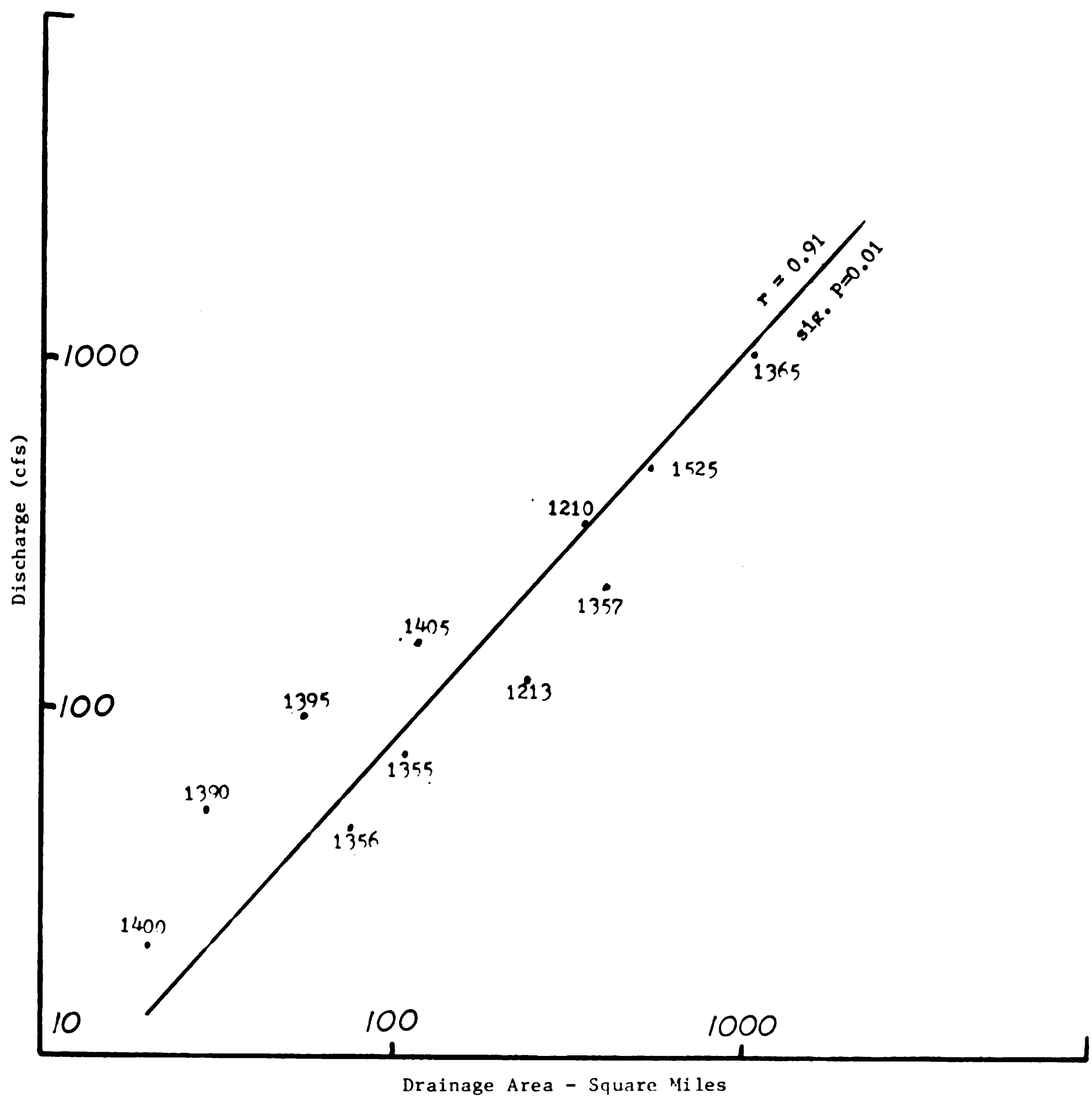


Figure 13.--Drainage Area--Discharge correlation for February, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

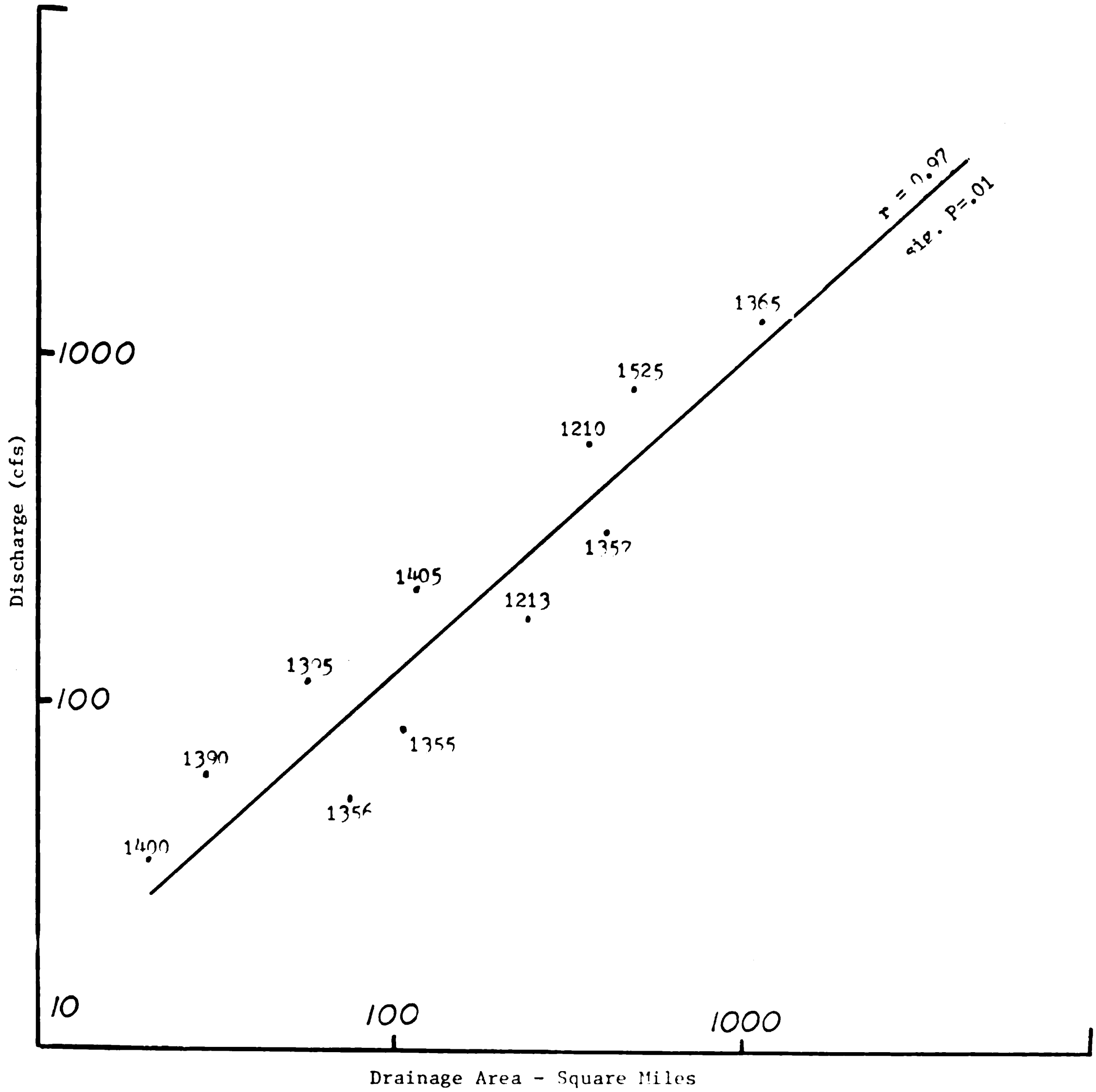


Figure 14.--Drainage Area--Discharge correlation for March, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

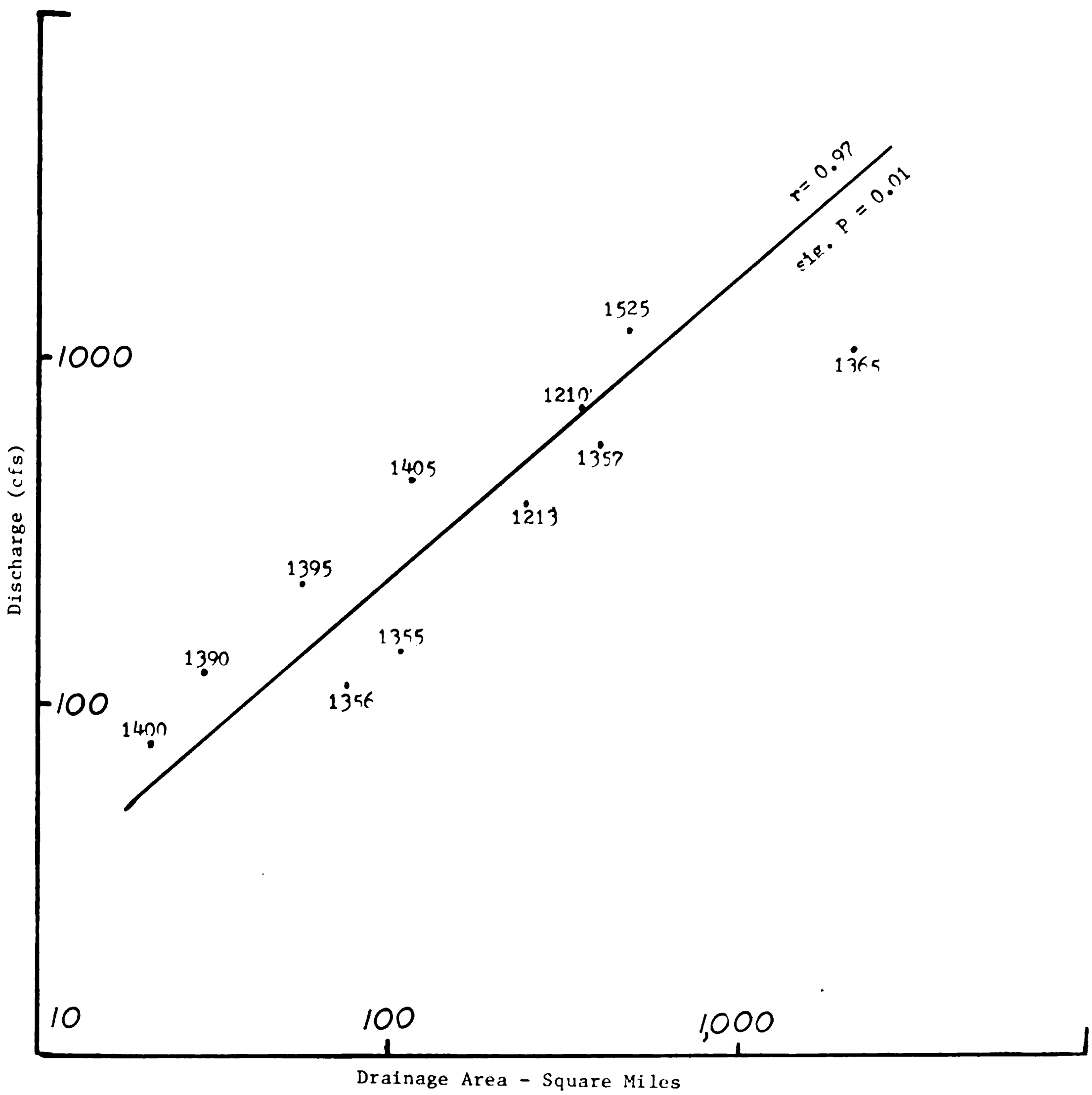


Figure 15.--Drainage Area--Discharge correlation for April, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

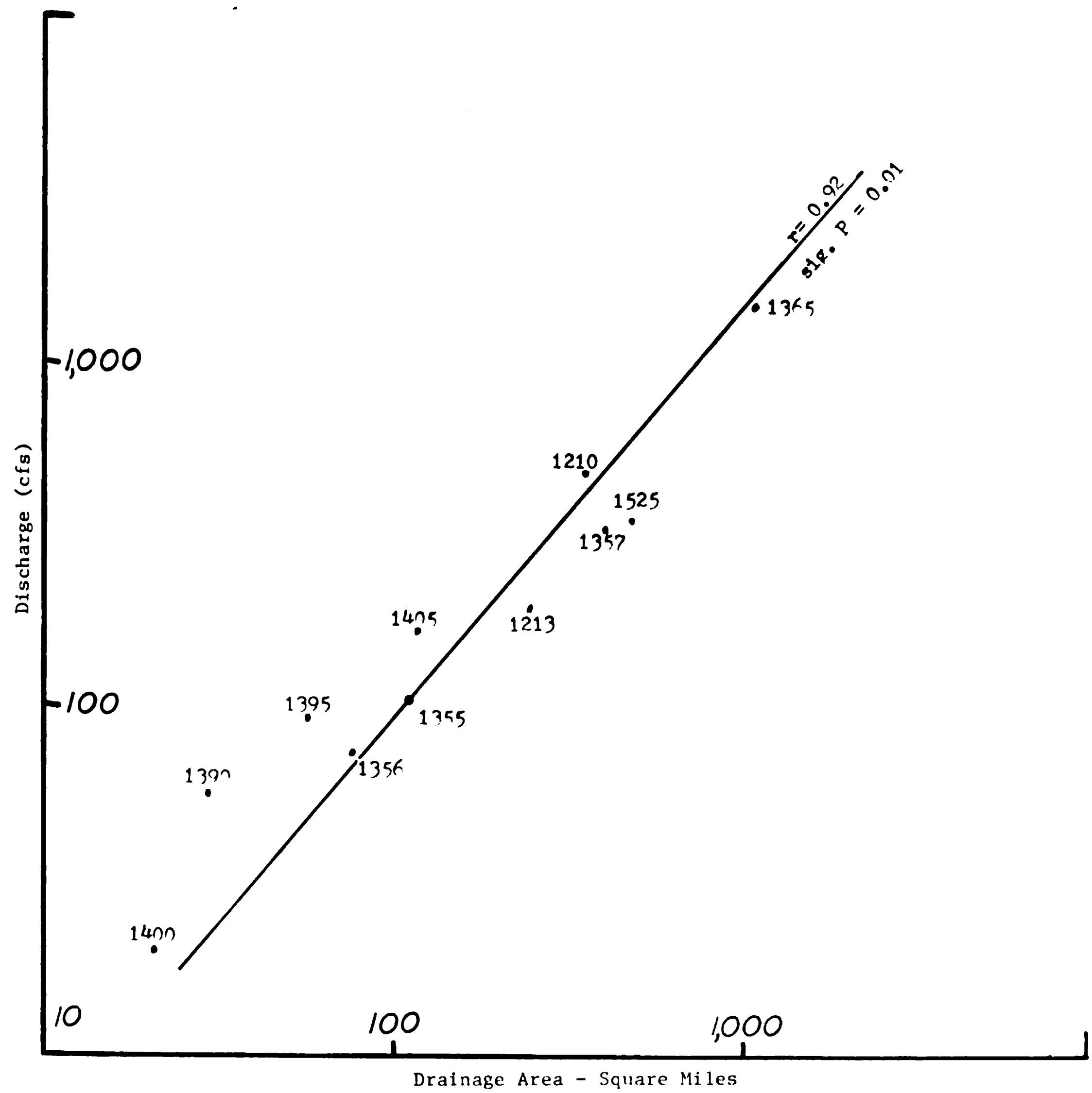


Figure 16.--Drainage Area--Discharge correlation for May, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

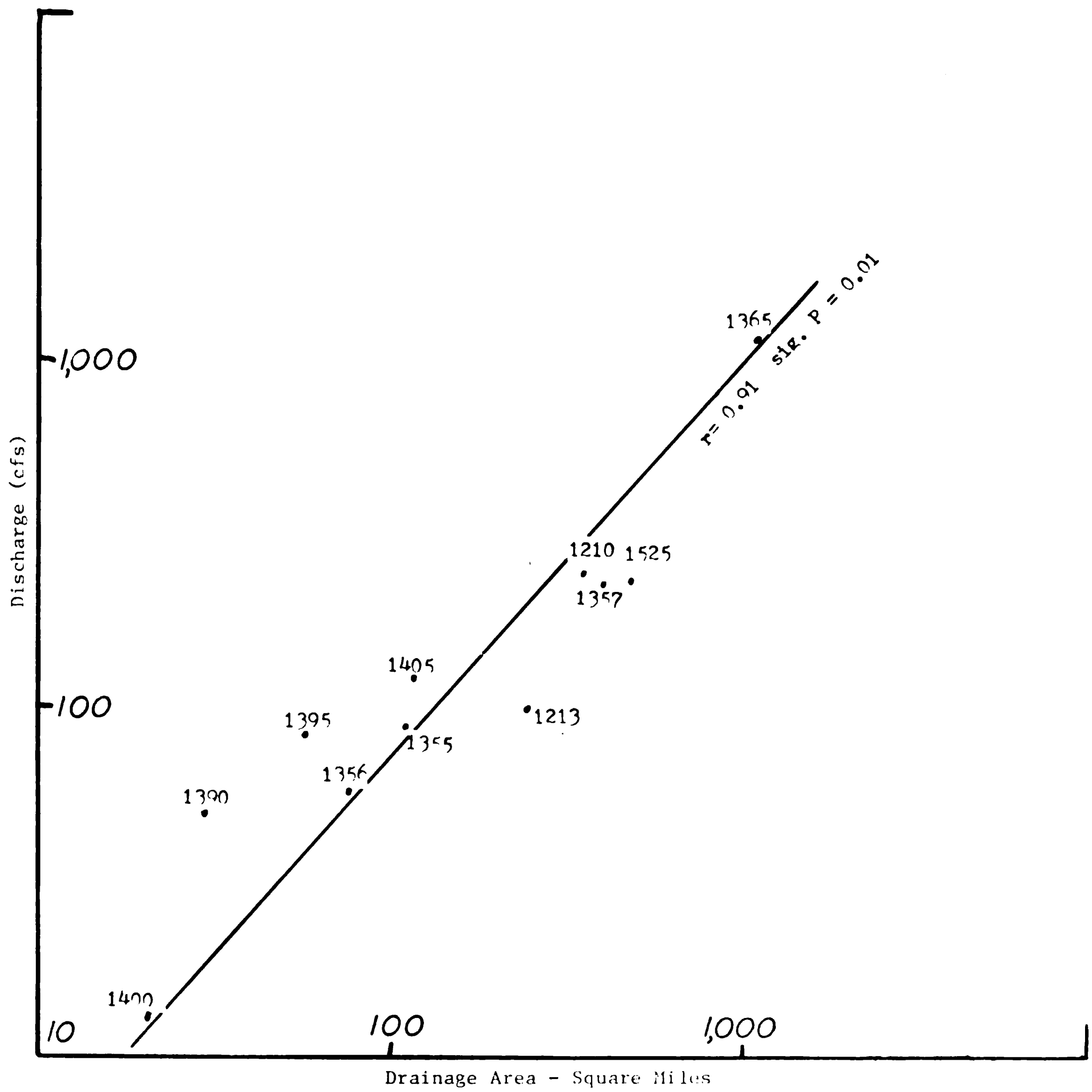


Figure 17.--Drainage Area--Discharge correlation for June, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

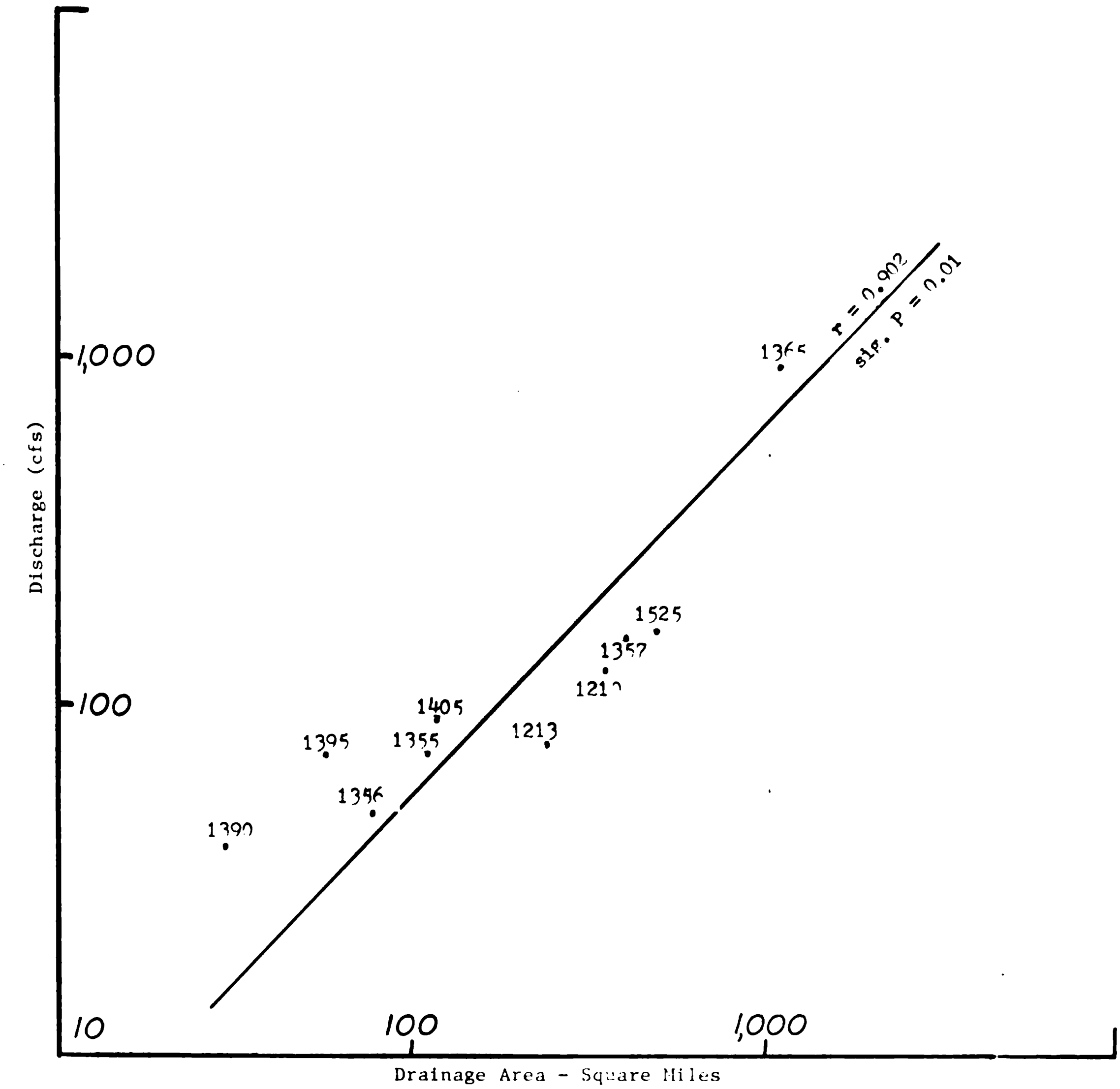


Figure 18.--Drainage Area--Discharge correlation for July, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

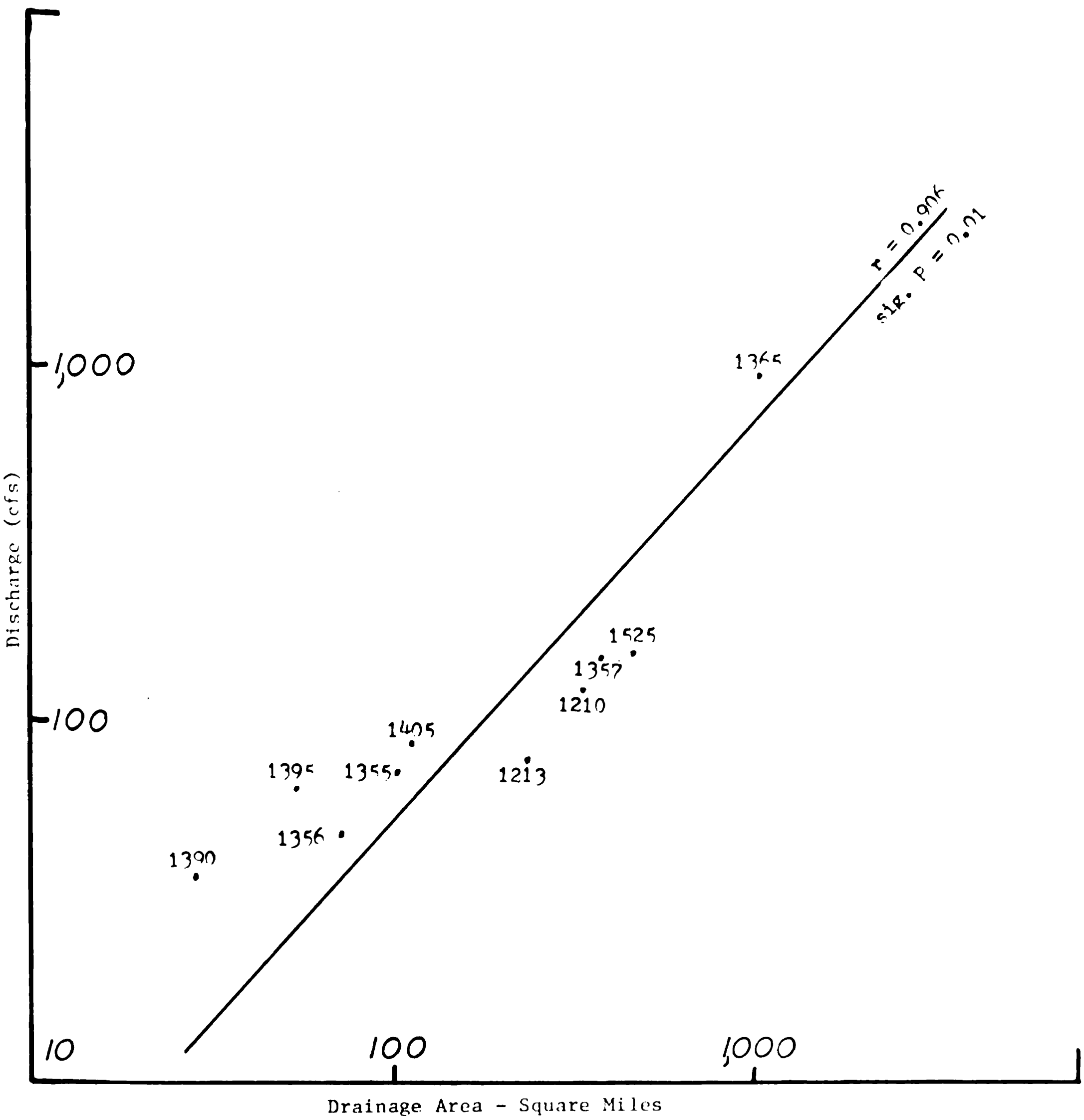


Figure 19.--Drainage Area--Discharge correlation for August, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

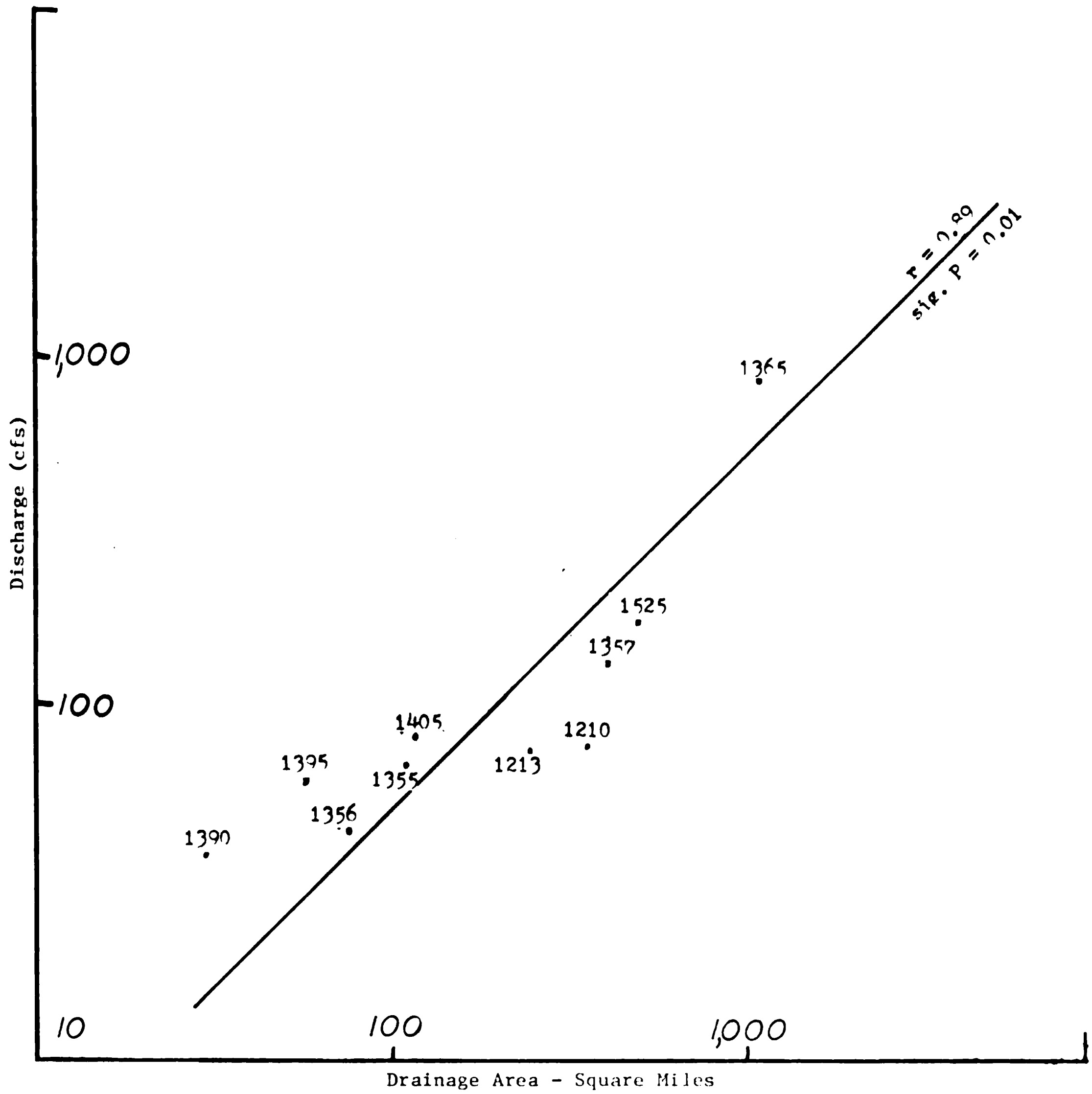
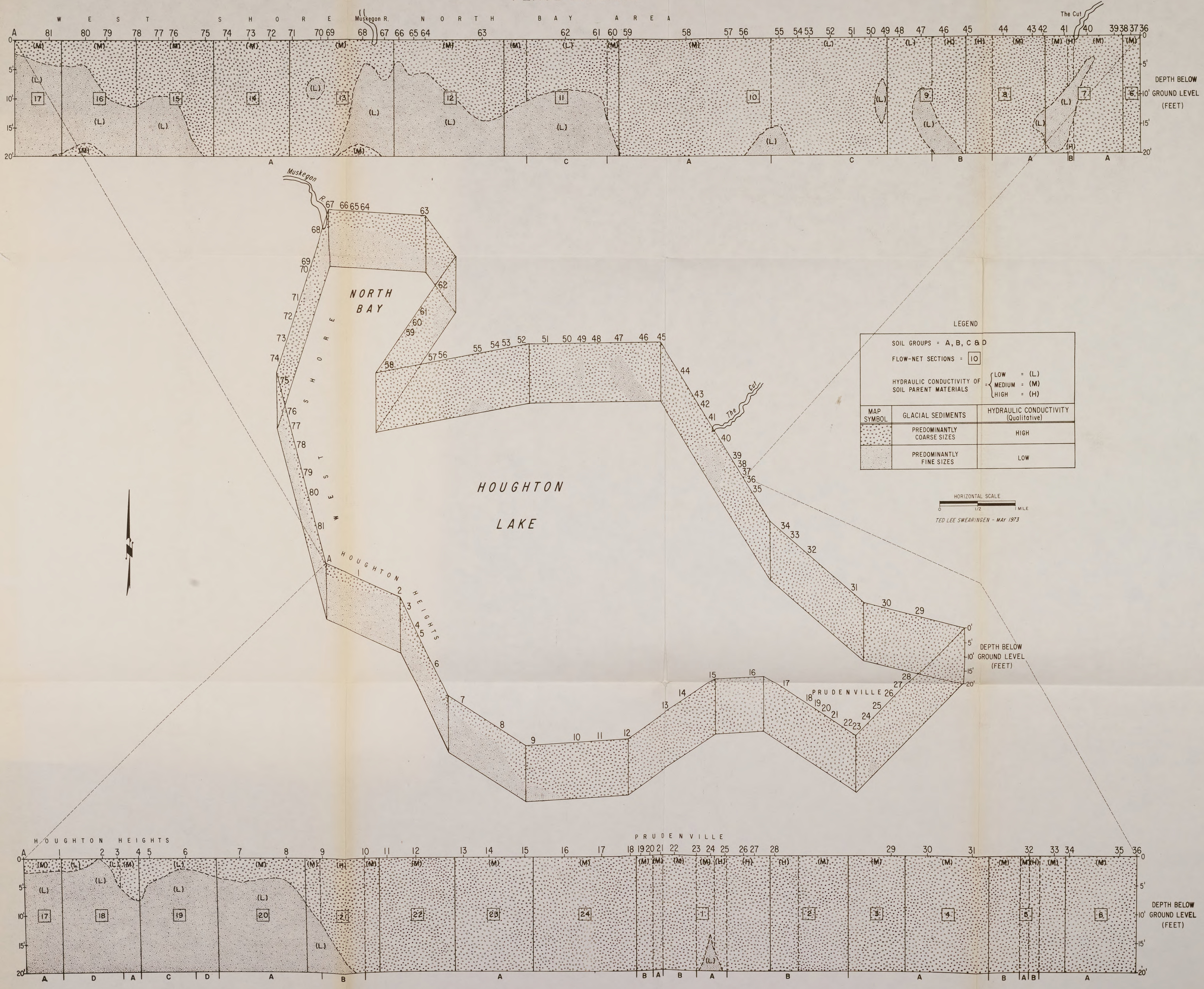


Figure 20.--Drainage Area--Discharge correlation for September, 1971. Data are from United States Geological Survey gages within a 50 mile radius of Houghton Lake. Numbers at each point are U.S. Geological Survey gage designations. Data were fit by simple linear regression, where r is the linear correlation coefficient and is significant at P = 0.01.

MAPS

HOUGHTON LAKE AREA
FLOW NET
SCALE IN MILES
0 1 2
Direction of ground water movement
1140 Equipotential lines (contour lines)
Flow lines
15 Flow net section numbers
GROUND WATER DIVIDES
Major
Minor
Probable
Compiled by -- K.E. Childs & T. Swearingen
Map number --
Date ------ 2/30/73
LYON
T.24N., R.4W.
LAKE
T.23N., R.4W.
MARKEY
T.23N., R.3W.
HIGGINS
T.23N., R.2W.
HOUGHTON LAKE
NORTH BAY
LONG POINT
THE MOUND
WHITNEY
THE HEIGHTS
SO HOUGHTON HEIGHTS
HOUGHTON LAKE
SUMMIT HEIGHTS
HOUGHTON BEACH
JOHNSONS RESORT
CRYSTAL BEACH
Prudenville
DENTON
T.22N., R.3W.
T.22N., R.4W.
BACKUS
T.22N., R.2W.
MUSKEGON RIVER BASIN
KNAPPENS
T.21N., R.3W.
TRIANGLE PARK
OAK GROVE
ALMEDA BEACH
Mert L.
Robinson L.
Sinkhole L.
Robinson Creek Flooding
Little Mud Lake Flooding
Backus Creek Flood
Backus Lake Flooding
Lake James
Barney L.
Denton Creek Flood
Ryan L.
Field Headquarters
Rollway
Slide
COUNTY GLADWIN

HOUGHTON LAKE SHORELINE FENCE DIAGRAM



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