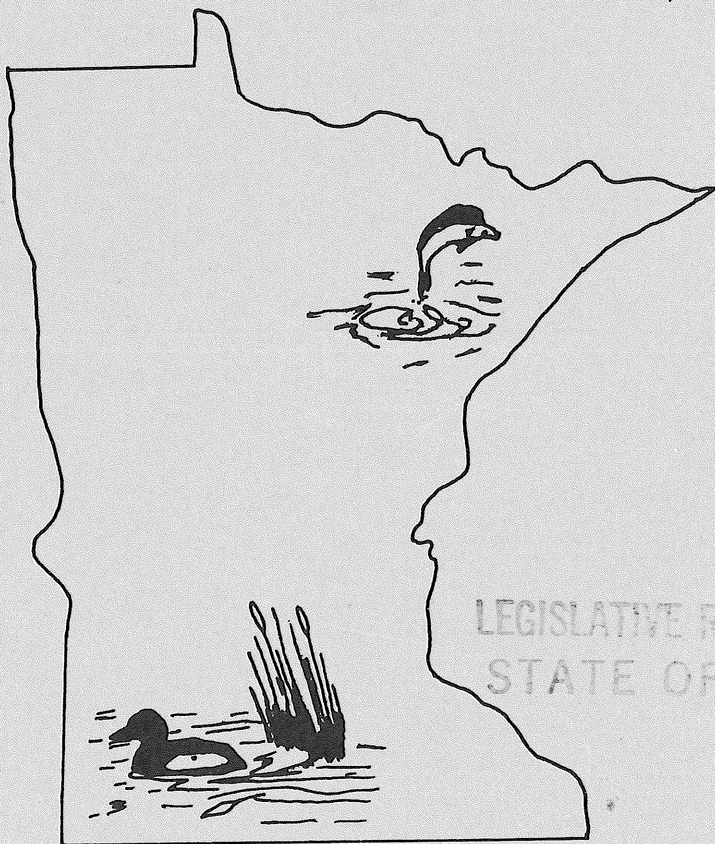
1126-77

BIOLOGICAL AND PHYSICAL CONDITIONS IN MINNESOTA'S STREAMS AND RIVERS AS RELATED TO PHYSICAL STRESS



DEPARTMENT OF NATURAL RESOURCES

DIVISION OF FISH AND WILDLIFE

ECOLOGICAL SERVICES SECTION

SPECIAL PUBLICATION 122

Minnesota Department of Natural Resources

Division of Fish and Wildlife

Ecological Services Section

Special Publication # 122

Biological and Physical Conditions in Minnesota's Rivers and Streams as Related to Physical Stress.

By: Arthur R. Peterson
Aquatic Biologist

PAGE

INTRODUCTION

Knowing what will happen to plants and animals present in streams and rivers when the physical characteristics are altered has become very important. It's well known that many species of plants and animals inhabit and are frequently abundant in rocky rapids, riffles, or pools and that some areas have few plants and animals. Some stream alteration practices can improve conditions for fish and invertebrates while others are detrimental and either reduce or eliminate plant and animal populations. Usually when this happens one or more physical features is changed to the extent that plants and animals have difficulty in surviving, and this can be called physical stress. Compiling and analyzing existing data to illustrate the potential magnitude of physical stress in Minnesota's streams and rivers is the objective of this report.

Environmental stress on aquatic life can have a short duration, for example acute problems such as an accidental spill of a toxic material, or the stress may last many years, for example chronic problems such as an unstable substrate, excessive periodic water level fluctuation, or pollution from cities and towns. Various investigations in the past have collected good information on problems related to physical stress and will be used to illustrate the problems. Of the various factors which could be considered, the erosive force of water and the amount of water present, variation in the amount of water, light penetration, and characteristics of the soil are frequently important physical factors.

BACKGROUND FROM LITERATURE

General Background

Many of the variations in the quality of aquatic habitats is related to the existing physical conditions. At locations where numbers of animals and species are low, some form of environmental stress is present, physical, chemical, or biological. Many permanent alterations of the environment are physical and can range in effect from detrimental to beneficial.

Some of the best observations on the effect of the physical environment were made by Ward and Whipple, 1918, and are as follows:

"The size of bottom materials is an important condition of existence. In streams the current sorts the materials, leaving the coarsest in the swiftest current, and the finest in the most sluggish current. In the curves of streams, the current is usually swiftest on the outside, and most sluggish on the inside. Different animals tend to occupy the different kinds of bottom materials. Thus, the differentiation of bottom constitutes an important differentiation of conditions of existence. The bottom of a swift stream eroding sandy soil is very unstable and the fauna is very sparse. Such streams are essentially aquatic deserts and only a few burrowers are able to live in them. Sandy bottomed streams with a sluggish current have a luxuriant fauna of burrowers and flora of rooted vegetation. Rocky and stony streams have rich faunas of clinging and hiding animals. Bottoms of soft muck containing putrescible organic matter occur in the absence of current. The character of terrigenous bottom is an important condition of existence, chiefly where current or wave action is strong, and becomes of little or no importance where there is no movement."

"In streams, the strength of the current is a function of volume of water and slope of stream bed. The amount of sediment carried and the size of the sediment particles is determined by the strength of the current and by the character of the materials eroded. The character of the stream floor, the ventilation of the environment, and hence its gaseous content as well as turbidity, are determined by the same factors. In a comparatively straight stream the current is swiftest in the center at the top, and least swift at the sides near the bottom; the center of the stream bed has a current intermediate between the two. Thus, sluggish portions of streams may be swift enough at the bottom of the center to support some swift stream animals such as Hydropsyche and Heptageninae. There are back eddies about stones and other obstructions so that currents in streams are somewhat irregular."

Richardson's work on the Illinois River is quoted by Welch (1935), and he notes the following about water velocities in the river: "At ordinary high-water levels, the current of the river from Chillicothe to the mouth varies from 1 to 2 miles per hour, according to the slope of the bottom, the width of the bed, and the presence or absence of obstructions; and at the highest water it does not much exceed 3 miles per hour for any important distance. At ordinary midsummer levels the current rate per hour varies in different section from 1/2 miles to 1 mile. At lowest water, it drops, between Chillicothe and the foot of Peoria Lake, to as little as 0.29 mile per hour."

Following is Welch's (1935) summary of Needham's work on central New York streams:

"1. Ordinarily, the distribution of aquatic animals in streams is dependent largely upon (1) temperature of the water, (2) nature of the bottom, and (3) velocity of current.

2. In general, streams from source to mouth present two distinct types of habitats, (1) pools, and (2) riffles.

3. Riffle bottoms greatly exceed the pool bottoms in productivity.

4. Fishes in streams tend to seek the pools. The pools also act as catch basins for animals swept down from the riffles, these drift animals serving as food for the pool fishes.

5. Of the various types of bottom which lack the higher aquatic vegetation, silt bottom is most productive of small organisms; rubble, coarse gravel, fine gravel, hardpan, and bedrock produced successively less in the order mentioned.

6. Plant beds in streams, when they occur, markedly affect productivity. Stream bottoms supporting growths of aquatic plants were found to be over seven times more productive than were stream bottoms bare of vegetation."

Welch's (1935) comments about the distribution of plants in rivers is as follows:

"The larger aquatic plants usually do not occur in conspicuous quantities in streams except where the current is greatly reduced. In the slower water of stream edges, a narrow margin of aquatic plants may occur but usually with limited success. Some of the very slow, sluggish streams may become literally plant choked, maintaining a luxuriant flora composed principally of the submerged and floating types. Back waters and similar situations often produce great quantities of the higher plants."

Welch describes the effects of flood on the environment as follows:

"The eroding and scouring-out action of flood waters often have the effect of literally depopulating portions of streams. Injury and mortality may be very high at times of flood, an interesting instance of which is reported by Needham as follows:

"A net was used to strain the material being carried downstream during a high flood in Six Mile Creek near Ithaca, New York. The results were most illuminating. Practically every kind of aquatic organism which have been collected from this stream during the previous summer was taken in the net. The great majority were dead or injured by the grinding action of rocks and gravel which were being carried downstream. Many parts of insect larvae such as heads, legs, tails, and abdomens offered evidence of the destructive action of the high waters. Many aquatics such as blackfly larvae, Simulium, which are never taken drifting free in the current under normal circumstances, were collected, bruised and battered, as they were carried downstream. Bottom studies made after the flood had subsided showed but a fraction of a gram of organisms remaining per unit area."

Tarzwell (1937) notes that in the coolest portions of trout streams (difference about 10° F.) that the standing crop of benthos in riffles was lowest, range 65 to 77 percent of the crop in the warmer sections of the stream. Minnesota streams show similar differences of standing crops of benthos and fish between streams with cool and warmer water, Peterson (1975). Tarzwell also notes that streams which are frequently flooded have low standing crops of benthos when compared with streams that are rarely flooded. The crops of benthos in the frequently flooded streams were 12 to 24 percent of the benthos crops in the stable streams. Tarzwell also stated that "It appeared that the streams flowing through limestone formations or formations containing limestone were richer than those flowing over volcanic granite or other acid rock formations."

His table indicates that the water flowing over limestone has a total methyl orange alkalinity ranging from 101 to 129 p.p.m. and 44 to 70 p.p.m. over igneous rocks. Pools had lower standing crops of benthos than riffles. The data for benthos crops in pools and riffles in waters of various hardness is summarized in Figure 14.

Tarzwell (1936) shows the relative standing crops of benthos on various kinds of stream bottoms which are as follows:

"The data shows that the sand produce the fewest organisms. If sand is given the population rating of 1, the relative productivity of the other bottom types are found to be as follows: mar, 6; fine gravel, 9; sand and silt, 10.5; gravel and sand, 12; sand, silt, and debris, 13; gravel and silt, 14; *Chara* and silt, 27; *Potamogeton pectinatus*, 28; rubble, 29; coarse gravel, 32; *Chara*, 35; mucky areas, 35; medium gravel, 36; *Potamogeton filiformis*, 43; gravel and rubble, 53; sand and gravel with plants, 67, muck, sand, and plants, 67; moss on fine gravel, 89; moss on coarse gravel, 111; moss on gravel and rubble, 140; *Vallisneria*, 159; *Ranunculus*, 194; watercress, 301; and *Elodea*, 452. These relative populations ratings show clearly how food production in a sand section of a stream may be increased by a deflector which uncovers gravel and which produces mucky areas and plant beds." After stream improvement, the calculated total standing crop of benthos increased by a factor of 2.92.

EFFECTS OF PHYSICAL ALTERATIONS

Ward and Whipple, (1918), summarize the effects of man on the environment by pollution, as follows:

"Man has been a powerful agent in modifying fresh-water life. By hunting and fishing, he has exterminated many forms directly.

Through modifications of streams or shore for commercial purposes he has indirectly eliminated many more, and finally by polluting the waters with sewage and waste he has rendered extensive water areas almost devoid of aquatic life except bacteria and even incapable of supporting any other forms. Streams below great cities and in mining and manufacturing districts are aquatic deserts."

In addition to pollution, physical modifications have had some extreme effects on the environment. In the fisheries literature, dams, impounding water, channeling, stream improvement and floods are the most frequently mentioned types of physical modifications. When streams are improved more catchable sized fish are creeled, at least 200 percent, but where streams are channeled, the standing crop of catchable fish can decrease 85 percent, or in practical terms, almost nothing. If a stream's carrying capacity for fish is 100 pounds per acre, beneficial habitat improvement practices and detrimental channel modification practices could cause the carrying capacity to increase to approximately 200 pounds per acre or decrease to 15 pounds per acre.

When streams are improved, there is an increase in pool area, deep areas, gravel riffles, and bank cover at low flow which is accomplished by stabilizing the stream banks, narrowing the stream and deflecting the current against each bank in an alternating pattern. The principal recent references for stream improvement are Hale (1969), Hunt (1971), and White (1967). For the adverse effects of channeling on carrying capacity for fish are Hansen (1971), Congdon (1971), Bayless (1967), and Peters (1964).

In general, new channeling usually decreases a stream's capacity to hold fish at about 80 to 90 percent, but the channel's carrying capacity for fish might increase to 50 percent of its initial carrying capacity 15 years after modification (Bayless, 1967). Montana channeled streams had a carrying capacity which was 82 percent lower than natural streams (Peters, 1964).

Channel modifications such as ditching are accomplished by making the channel straighter, wider and shallower, and the banks frequently have no protection and erode readily. An increase in the size of fish populations can occur after the decrease caused by ditching, but will take several years and will ordinarily not be more than 50 percent of the initial carrying capacity unless correct stream improvement practices are applied. The effect of some modifications might be masked by fish moving in from unmodified adjacent areas, especially when the modifications are a small portion of the stream's length.

Emerson (1971) documents the physical changes in the Blackwater River in Missouri which are channeled 60 years before his study. The channel length decreased from 53.6 km to 29 km, and the gradient increased from 1.67 meters per kilometer to 3.1 meters per kilometer. The present channel's cross-sectional area increased from 38 square meters when newsly dredged, to a size ranging from 160 to 484 square meters. The channelized portions of the stream have increased in width and depth one and 0.16 meters per year since channeling.

Bridge lengths have progressively increased from 15.2 meters to as much as 124.2 meters. Several bridges have failed from bank erosion. He notes that the present shannel has displayed no tendency to resume meandering, and that the fish population in the unchanneled portion is 256 kilograms per acre and 51 kilograms per acre in the channeled portion, or 19 percent the amount in the unmodified reach.

In the main channel of the Missouri River where portions have been channelized, there was 4.7 fold of increase in turbidity, and the dissolved oxygen, bottom fauna and invertebrate drift was 81, 14, and 11 percent of the respective amounts in the unmodified channel. Table 1 was constructed from data presented by Morris (1968). He also notes that the density of benthos (invertebrate) was a small proportion of the amount found in the Illinois River, 0.43 pounds per acre as contrasted to 261 pounds per acre. He noted this low standing crop was associated with shifting substrate, siltation, fluctuating water levels, lack of vegetation, and a swift current.

Wickliff (1937) presents some data on the standing crops of benthos in natural pools and impoundments in Ohio streams. In the data presented, pools created by dams had about 241 bottom organisms (range 0-1000) per square meter, while natural pools had 538 bottom organisms (range 200-1750) per square meter. He recommended that riffles in streams should be retained, low dams should not increase pool depths much over 40 inches, all the water in a pool should be circulated, that tree stumps be left in waters shallower than 15 to 20 feet, and that mineral soils along the shore such as gravel and rubble be exposed. He notes that fluctuating water level affects the production of vegetation and spawning grounds of fish. Wickliff also notes that vegetation may become so abundant that oxygen is depleted when days are not bright and sunny.

Table 1: Difference between biological, physical, and chemical conditions in channelized and unmodified portions of the Missouri River main channel.

Item	Not Modified	Channelized
Total Alkalinity	170 - 200	176 - 185
Dissolved oxygen	8.0 - 8.7	6.2 - 7.4
Temperature	69 - 78 F	71 - 79 F
Benthos		
Bottom samples	0.43 lbs/acre	0.06 lbs/acre
Drift	68.3 gm/ac. ft.	8.0 gm./ac. ft.

PHYSICAL VARIATIONS

General

Any stream or river can exhibit a wide range of physical conditions, especially when it is viewed from the source to the mouth. Ordinarily, waterways are named creeks, brooks, runs, or rivers, according to their size (width). This is usually the width of the waterway near the mouth. In a series of measurements on tributaries in the St. Louis River System, creeks ranged from 2 to 30 feet wide, averaged 12 feet and rivers tributary to the St. Louis River had an average width of 65 feet, and were ordinarily more than 30 feet and less than 100 feet wide. The word stream is a general term, used to designate any body of flowing or running water, but in fisheries work, the word stream is most commonly used in work associated with creeks. A brook is a term sometimes used for a creek which has a smaller than average width. A run is a creek with a higher than average water velocity (1.0 ft. (sec).

Table 2: Widths of various kinds of waterways.

Term	Width
River	
Large	Over 100 feet
Small	30 to 100 feet
Creeks	
Creeks and Runs	2 to 30 feet
Brooks	2 to 12 feet
Small Waterways (Brooklets, streamlets, riverlets)	Under 2 feet

Since very few waterways are alike and their topographic locations can vary considerably, it is useful to know how a typical stream might vary from its source to its mouth. A typical stream course can be divided into four distinct parts, and they are (1) the upland part which may be a waterway that is likely to be intermittent except where bogs and swamps are present, (2) steep sloped portion of a stream at the upper end of the valley tend to be intermittent except at the lower end where it cuts into the water table, (3) the less steeply sloped portion in the main part of the valley usually has a permanent flow and increases in size from ground water seepage and springs, and (4) the portion in the valley's lower end which has a flat gradient and meanders out of the valley to the outlet. When tributary streams enter the valley containing a major river they also tend to parallel the course of the river before they reach their mouth.

Rivers and streams gain water where they cross, or are in the ground water table and lose water from evaporation and seepage where the water table is lower than the stream bed. Where precipitation ordinarily equals or exceeds evaporation, extensive bogs and marshes are likely to occur in poorly drained uplands and are the sources of many streams and rivers. Where evaporation is higher, a considerable portion of the upper part of a stream is likely to be intermittent before the flow becomes permanent. In high, relatively flat dry uplands, permanent streams only occur where impervious formations, such as shale, are close to the surface.

Permanent flows usually start where ground water enters the stream bed, and the stream cuts through the ground water table. Where the stream flows over impervious bedrock, streams gain water. Streams frequently lose water where convex profiles occur, and gain water where profiles are concave. Convex stream profiles usually occur at the rim of the upper end of the valley, and concave slopes occur at the foot of the steep valley slopes of many streams.

In broad, well defined deep valleys with large rivers, many small permanent streams originate or gain most of their water at the edge of valleys (concave profiles). Streams sometimes meander through the valley adjacent and are nearly parallel to the main river before they reach their mouth. If the valley floor is composed of extremely permeable sand, gravel, and rock, a stream might lose a considerable portion of its water in the middle part of its course in the valley, but will regain it, plus some additional water, where the stream bed enters the ground water table in the lower part of the valley.

FLOWS

Stream flows are lowest in the western edge of the state (runoff one to two inches a year) and highest along the eastern border (runoff six to ten inches per year). Ordinarily the highest flows occur in the spring, usually April and occasionally March or May, and then decline to low in late summer and early fall, August and September. In the fall, flows increase until November and then decline and reach another low in late winter, usually January and February. Runoff from spring and early summer rains sometimes increases flows to the extent that they equal or exceed the spring high flows. On the southern edge of the state, high spring flows usually occur about a month earlier, from mid-March to mid-April.

To effectively compare the magnitude of flows in various streams and rivers, the flows must be reduced to a relative flow measurement. For example, the monthly or daily flows were divided by the long term average flow to compare the average monthly flows in rivers. Flows were nearly average in most parts of the state from October 1970 to September 1971, so the relative monthly flows were calculated for several gauging stations by dividing the monthly by the long term average flow. The results are summarized by watershed in Table 3.

Table 3: Relative 1/ magnitude of monthly flows by season in Minnesota River Basins in an average year (October, 1970 to September 1971)

Drainage System	Spring High	Summer Low	Fall High	Winter Low
Lower Mississippi	2.25	0.50	1.38	0.45
Minnesota	2.66	0.12	1.50	0.14
St. Croix	4.27	0.26	1.49	0.30
Upper Mississippi	3.25	0.33	1.09	0.46
Red River	3.90	0.45	0.81	0.38
Lake Superior	3.62	0.24	1.37	0.26
Rainy River	2.74	0.23	1.44	0.32
Average	3.24	0.30	1.30	0.33

1/ Highest monthly flow divided by the average flow.

As compared to the average flow, the monthly average flows in the spring are 3.24 times higher, low summer is 30 percent of the average, the maximum fall flow is 1.30 times higher than average, and the late winter low is 33 percent of the average flow. The minimum and maximum daily flows are more extreme, about 0.25 to 5.0 times the average flow. Table 3 shows that, in an average year, streams in the St. Croix River, Red River and Lake Superior drainages have the highest relative flows in the spring, and that the other drainages have average or lower than average relative flows in the spring. Since the Red River, St. Croix, and Lake Superior drainages have the most runoff, water flow problems are likely to be more extreme.

Hynes (1972) notes that floods 1.2, 1.4, 1.6 and 1.8 times deeper than bankful depth occur once every 5, 10, 25, and 50 years respectively. Depth at average flow is 35 percent (range 20 to 45 percent) of bankful depth. Average flow is about 12 percent,and range 7 to 28 percent of bankful flow, which occurs every 1.5 years. Flows 1.6, 2.1, 3.1, and 4.2 times the bankful flow occur every 5, 10, 25, and 50 years respectively. Average flows in Minnesota appear to have a similar relationship to bankful flows (flood stage). Average flows are 6 to 23 percent of bankful flows in Minnesota.

High flows occur most frequently from March through September, as runoff from melting snow and intense spring and summer rainstorms. Reocrds of the extreme high flows show that they occurred most frequently in April (52 percent) and least frequently in July, August and September, 10 percent of the time.

Table 4: Months when the extreme high flows occurred (percent of the records).

Month	Percent
March	5.7
April	52.5
May	18.4
June	13.5
July	5.7
August	2.1
September	2.1

Flows in some rivers are subject to considerable regulation, which is largely determined by the storage capacity of reservoirs on them, while other rivers have relatively natural flows which are sometimes delayed somewhat by temporary storage in lakes. Some rivers, such as the St. Croix, have nearly normal seasonal flows, but some have diurnal fluctuations caused by hydroelectric power plants. When the hydroelectric plants use a large proportion of the daily flow, water levels in and below the impoundment are likely to vary noticeably. Daily variations of a foot or two in water levels are not uncommon in small hydroelectric impoundments, and are occasionally larger.

To illustrate the seasonal differences, Table 5 was constructed, showing flows at gauging stations where flows are modified significantly by discharges from impoundments and where they are not. Unregulated flow vary more than regulated flows. In the unregulated streams in Table 5 (St. Croix and Big Fork) about 29 percent of the water was discharged in April, and in regulated streams 13 to 19 percent of the water was discharged in the April high flow periods, 10 to 16 percent lower. The differences between low and high flows are not as extreme where flows are regulated and tend to be higher where flows are not regulated. The discharge from the headwaters reservoirs as reflected in the Mississippi River flows at Grand Rapids, produces a high typical fall and winter flow, while on the Rainy River flow pattern is normal, but the high spring peak is reduced and extended over a longer period of time.

Table 5: Differences in the relative volume of water discharged where water is stored for future use (Mississippi and Rainy rivers) and unregulated except for temporary storage as in lakes. (1970-1971)

		Percent of Total Volume Discharged		
Month	St. Croix	Mississippi (at Grand Rapids)	Big Fork	Rainy
October	6.0	2.2	8.2	7.8
November	11.4	7.3	8.9	12.7
December	5.8	9.0	4.3	10.7
January	4.1	12.4	2.4	7.5
February	4.1	13.9	1.8	5.8
March	5.9	15.7	1.4	5.2
April	29.2	18.6	29.3	12.3
May	13.3	7.0	21.4	12.3
June	7.6	5.5	14.2	12.7
July	4.4	4.0	4.1	7.0
August	3.9	2.0	1.8	3.6
September	3.8	2.4	2.2	2.6
Range	3.8 - 29.2	2.0 - 18.6	1.4 - 29.3	2.6 - 12.7

Water Velocity Relationships

In late summer and early fall, when water flows are lowest in smaller streams and rivers, water velocities are lowest in pools (below 0.8 feet per second), and highest in riffles and rapids. Riffles average 2.0 and rapids average over 3 feet per second. Erosion of sandy bottoms doesn't occur at velocities under 0.8 feet per second, average gravel bottoms resist erosion at velocities from 2.0 to 2.6 feet per second, and rubble and rocks 3 to 18 inches in diameter resist erosion at velocities from 3.0 to 5.0 feet per second. Where stream beds are stable, and excepting clay bottoms, sandy and silty bottoms are found in pools, gravel bottoms in riffles, and coarser rocky bottoms in rapids. Depending on its cohesiveness and particle size, clay can resist erosion at velocities from 0.9 to 1.0 feet per second.

When stream beds are not stable, water velocities are frequently intermediate (1.0 to 2.0 feet per second) between those found in riffles and pools. For example, many streams have coarse sandy bottoms, and sand particles can be observed being moved along the bottom, or move at the slightest disturbance.

Since stream velocities are likely to vary considerably between locations, some idea of the range of velocities which might be encountered is necessary. A large number of measurements of stream velocities is available for all sizes of rivers and streams for the St. Louis River Watershed and other streams tributary to Lake Superior (North Shore streams). Observed velocities ranged from a trace to less than 5.5 feet per second, with means being 0.93 and 1.26 feet per second in the St. Louis and North Shore streams respectively. Water velocities more than 3 feet per second are relatively uncommon. In the steep sloped North Shore streams, they were less than 5 percent of the observations. About half of the observations were made in pools, and half in faster water such as riffles.

Higher water velocities are more likely to be encountered in larger rivers than in small streams, but the range of velocities is approximately the same. At 124 seining stations in the St. Louis River watershed, the following conditions were tabulated from the 1941 field notes.

Table 6: Percent occurrence of water velocities by stream width.

Width (feet)	Average Velocity	(n)	Percent under (feet per second) 0.5	1.0	2.0
Under 20	0.59	(40)	53	81	100
21 - 40	0.58	(34)	46	86	100
41 - 100	1.08	(25)	20	40	100
Over 100	1.08	(19)	20	40	100

Note that at the wider waterway sampling stations the velocities are more than one foot per second. Moyle (1940), Johnson (1968), and Peterson (1962) investigated the Upper Mississippi and larger tributaries, and their data summarized in the following table shows larger streams tend to have higher water velocities.

Table 7: Water velocities and widths in larger Mississippi Watershed Rivers.

River	Average	Range	Width
Mississippi			
Winnibigoshish to Pokegama Reservoir	1.39	0.3 - 20	91
Pokegama Reservoir	-	tr. - 0.6	-
Grand Rapids to Brainerd	1.96	1.0 - 3.0	183
Brainerd to St. Cloud	2.15	1.1 - 3.8	400
Crow (Lower)	-	0.43 (max.)	75
Crow Wing			
(Above Nimrod)	1.3	-	150
(Near Mouth)	0.74	-	250
Leaf	1.5	-	80
Sauk (near mouth)	1.4	-	104

Water velocities are higher at high river and stream stages than they are at low stages, so both water depths and velocities increase as stream flows increase. Per foot of river stage increases, the increase is least where overall stream slopes (gradients) are least. Higher velocities are associated with higher slopes. King (1929) describes the effect of high and low river stages, and says that "At low stages the water surface conforms in a general way to the slope of the stream bed, and therefore, has a continually changing slope equal to the average grade of the stream bed."

In a stream where the average depth equals the width, the water velocities will be much higher than in a stream where the average depth is a small percentage of the width, because there is less bottom which can cause friction. So when water depth increases from increased flow, the water velocity increases. Increasing the slope will also increase the water velocities (see Table 8).

The relative amount of friction caused by the shape of the cross section can be determined by dividing wetted perimeter (length of the stream bed) in a cross section across the stream into the cross sectional area.

Table 8: Water velocities 1/ at various river stages and slopes in a river channel 100 feet wide with 1:1 bottom slope.

Average water depth	Average velocity (feet per second) Stream Slope Ft./mile			
	0.26	1.5	3.0	5.0
1	0.4	0.9	1.2	1.5
2	0.5	1.4	1.8	2.3
3	0.7	1.7	2.3	3.1
4	0.8	2.3	2.8	3.7
5	1.0	2.4	3.2	4.3
6	1.1	2.8	3.7	4.7
8	1.3	3.4	4.3	5.6
10	1.5	3.6	4.9	6.4

1/ Calculated using the Manning Formula $v = \frac{1.486}{n} r^{0.67} S^{0.5}$

where n = 0.030, 4 - hydraulic radius or wetted perimeter divided by the cross section area, and S = slope = (Ft/mile)/5280.

Irregularities of any kind, such as the character of the soil, increase the turbulance and friction between the soil and water and decrease water velocities. This is usually expressed as a coefficient of resistance (n) and in the Manning formula an increase in (n) means an increase in resistance. Some of the common ranges of values of (n) which are used are as follows:

Ordinary Range		0.025 - 0.035
Straight ditches:	fine textured soils	0.017 - 0.025
	stony beds and weeds	0.025 - 0.040
Straight natural channels:		
	no pools, rocks, or weeds	0.025 - 0.033
	rock and weeds	0.035 - 0.050
Sluggish river reaches:		
	rather weedy or with pools	0.050 - 0.080
	very weedy reaches	0.075 - 0.150

Stream bed conditions increasing or decreasing this coefficient will cause a corresponding increase or decrease in water velocity when other conditions affecting velocity are not changed.

Water Depths and Widths

Many streams and rivers have remarkably uniform channels, depth and width, while others can exhibit a wide range of depth and width characteristics in relatively short segments of its course. Usually the width and depth of streams increases from the source to the mouth. Leopold (1935) demonstrated that the general formulas, $d = cQ^f$ and $w = aQ^p$ illustrate the relationships and depths and widths respectively. In these formulas d = average depth, w = width, Q = average discharge of the stream, c and a are the intercepts of the lines where Q = 1, f and p are the slopes of the lines and have a value less than 1.0. Table 9 is a summary of the various data presented on many streams and rivers. For the stream as a whole, the value of the coefficient p is ordinarily about 0.50, but can vary.

Table 9: Relationship of average stream width and depth to average discharge (flow).

Average Discharge (c.f.s.)	Average Width (ft.)	Average Depth (ft.)	Calculated Velocity (ft./sec.)
10	15	1	0.7
100	50	2	1.0
1,000	160	4.5	1.4
10,000	500	10	2.0

p = 0.5 and a = 4.5 where $w = aQ^p$ or width = 4.5 times the square root of the average flow.

Some rivers and streams are reasonably straight, but the bottom is not. Deep areas or pools and shallows or riffles tend to be evenly distributed and occur at a distance equal to 5 to 7 widths of a stream. Where pools and riffles are present they are usually located where fairly steep gradients are present and where both sand and gravel are present. Pools are frequently described as being shallow, 1 to 2.9 times the average depth. Deep pools are more than three times the average depth. So riffles can be described as being shallow, and less than the average depth of the stream. In smaller streams and rivers, riffles and rapids are shallower than two feet, average about 1 foot. In pools the maximum depth is about 3.5 times more than it is in riffles, ordinary range 2.2 to 4.7. An average pool depth is about 60 to 70 percent of the maximum depth. In a stream where pools and riffles are evenly distributed, the average depth is about 1.6 times the maximum depth in riffles.

Leopold (1956) notes that western ephemeral streams, dry washes with bare mineral soil banks and beds adjust their width and downstream velocities more readily than average river channels, and carry a larger suspended sediment load. This means the banks of streams which are resistant to erosion will adjust their depth more readily than their width when flows increase. This depth adjustment can be upward or downward or both. Dams or hard sills across streams only permit upward adjustments of river depths so flooding could occur more frequently where fine textured soils comprise the bulk of the stream bed materials.

Normally we might think of a meandering stream course as occurring in the flat part of a valley, but stream meanders can occur where stream gradients are quite high. Langbien (1966) notes that nearly ideal meanders were produced in the laboratory on sand. Note that sand has a relatively homogenious particle size. Langbien (1966) also notes that where river bends are present, the energy dissipation tends to be equalized throughout that section of stream, but where this equalization occurs, larger than normal differences in streams bed elevation occur. Where there is a large contrast in particle size such as sand and gravel, pools and riffles are formed, and the energy of the stream is dissipated in the less erodable gravel bottomed steep sloped riffles where water velocities are highest. The conclusion is that energy is dissipated in the bends, curves, and shoals of a stream. Langbien presents data that illustrates the foregoing which is summarized in table 10.

Table 10: Difference between a curved and meandering reach of stream in Wyoming where the discharge is three quarters bankful.

Item	Straight Reach			Meandering Reach		
	Average	Range	Slope Correlation (r)	Average	Range	Slope Correlation (r)
Depth (ft.)	1.92	1.52-2.29	-0.21	2.17	1.25-3.77	-0.85
Velocity (ft./sec.)	2.81	2.12-3.67	+0.52	2.72	1.63-4.10	+0.95
Slope (ft. per 1000)	1.38	0.30-2.24	----	2.05	0.27-3.97	----

In the meandering stream, the steeper slope produced the same water velocities by adjusting the slope and depth. An increase in depth decreased water velocity in the meandering section, but in the straight reach where there was a small variation in depths, increases in slope were only partially correlated with increases in water velocity. In the meandering reach there was a good negative depth and positive velocity correlations with the stream's slope at various locations. Note that in both the straight and meandering (curved) reaches the average depth, velocity, and range of velocities were nearly equal, but an average slope, range of depths uncurved in the meandering (curved) reach were not.

Langbien (1966) also notes that meanders are a common feature of rivers, whereas, straight reaches of any length are rare, and therefore a temporary stream state. He also notes that meanders tend to move downstream. Leopold (1953) notes that channel bottom roughness tends to decrease going downstream, for example gravel to silt, and that it varies from stream to stream. The channel slope also decreases in a downstream direction, and the rate of decrease is related to the amount of channel roughness. Homogenious soil particle sizes are most likely to occur in the lower part of a stream's course so the chance that meanders will occur is higher.

Pools and deep areas are formed three ways, and they are by plunging flows of water, by obstructions in the channel, and by changing the direction of flow. Illustrations of the three types are, (1) plunge pools below waterfalls, dams and road culverts; (2) scoure holes below trees in the water, and between bridge abutments; and (3) river and stream bends. Plunge pools are about 1.25 times deeper than the height of the distance between the tailwater elevation and the water surface before it begins to fall. Scoure holes are usually formed under trees where stream bed soils are easily eroded, and the increase in depth is not more than an amount which is proportional to the relative decrease in stream width, plus the diameter of the obstruction (tree) in the water.

Ordinarily, the sharpest stream bends have the deepest water and the straightest stretches have the shallowest water. In the Mississippi River above Pokegama Reservoir where the average discharge is 512 c.f.s. per year at low flow (about 50 c.f.s.), straight riffles had a maximum depth of 1.5 feet. In curved stretches where course changed 22 degrees, the maximum depth was five feet, 10 feet at 55 degrees, and 15 feet at 80 degrees. The course change was measured by measuring the angle formed by tangents drawn from where the curves started and ended. The equation for the line from the data is $y = 1.5 + 0.164X$ where y = the maximum depth in feet, 1.5 is the maximum depth in the straight stretch, 0.164 is the slope of the line and x is the course change in degrees.

This equation can be used in a general form $y = a + 0.164X$ where a equals the depth in shoals or riffles. Since pools are about 3.5 times as deep as shoals or riffles with a range of 2.2 - 4.7, the change in course is about 15 degrees, range 7 to 22 degrees. The literature indicated that pools tend to be equally spaced at 5 to 7 times the stream width, so the tangent of the angles of current deflection would be 1/5 and 1/7 or a 8 to 30 degree deflection, which is within the 7 to 22 degree calculated range.

A current direction change of 15 degrees is small compared to the amount encountered in a meandering stream, average depth about 7 feet at a 30 degree course change in the data available. So a course change of 15 degrees is likely to be typical of a pool and riffle area where the channel alignment is reasonably straight. The stream length divided by the straight line distance should be less than 1.5 to be considered straight.

Extent of Turbidities and Effect on Dissolved Oxygen

There is a considerable amount of variation in the amount of light that penetrates water between seasons, years, various parts of the state, and in various parts of a stream or river. Light penetration is ordinarily expressed as p.p.m. of turbidity, volume of suspended material in water, and less frequently as transparency, usually secchi disc visibility. The turbidity in a waterway can be caused by several things, either signly or in combination, such as a colloidal brown organic stain, finely divided organic debris, or larger suspended organic and inorganic particles when the water velocity is high. Brown bog stained waters are ordinarily restricted to the northern part of the state where water is soft. These colloidal brown stains usually disappear when water becomes hard. Finely divided organic particles occur in larger concentrations in rivers where adjacent land is used for agricultural purposes, such as in the Minnesota and Red River of the North. Suspended larger inorganic particles occur most commonly where water velocities are high, and stream bed and/or banks are composed of finely divided soil particles such as sand and clay.

To illustrate the magnitude of year to year and seasonal variations in turbidity, table 11 was constructed from the more extensive records available. Ordinarily, one might expect that turbidities would be highest in the spring when the flows are highest, but the table shows that in many rivers the turbidity is highest in the summer when flows are relatively low, that this condition is most extreme in the state's agricultural region, and that most rivers have relatively low minimum turbidities that are most liekly to occur in the winter. In the forested region, seasonal turbidities are what might be expected unless bog stained waters are being discharged into them, high turbidities in the spring, low turbidities in the summer and winter, and intermediate in the fall. In the records examined, the highest turbidities were found in the Minnesota and Red Rivers, and lowest were found in the St. Louis and St. Croix Rivers. Apparently rivers such as the St. Croix which ordinarily has a considerable amount of bog stain in it, are clearest in the winter when frozen bogs don't discharge as much water.

Annual median turbidities ranged from 3.9 to 35 p.p.m. and the seasonal range of turbidities was from 3.6 to 7.3 p.p.m. in the clearest (St. Louis), 12 to 94 p.p.m. in the Red River, and 11 to 80 p.p.m. in the Minnesota River, the most turbid.

Turbidities are likely to increase from a stream or river's source to its mouth from discharges from turbid or bog stained tributaries, bank or stream bed erosion, and wastes from cities and towns, but they also tend to clear. The Mississippi River, from its source until it leaves the Minnesota Broundary Waters, is a good illustration. A series of data gathered from 14 sampling stations in 1967 to 1968 shows that, at its source, the turbidity was 3 p.p.m. and below Winona, about 650 miles downstream, it had increased to 26 p.p.m., but between the two locations it increased to an initial maximum of 20 p.p.m. from bog stained river discharges above Brainerd, decreased to 11 p.p.m. above Anoka, increased to 16 p.p.m. at the Minneapolis water intake from the Crow River, increased to 34 p.p.m. below St. Paul from wastes and the Minnesota river, then decreased to 15 p.p.m. below Lake Pepin, and increased below Winona.

The extent of median yearly variations in turbidity are greater than the seasonal variations in clearer streams in the forested region, but yearly median variations are about the same as seasonal variations in the southern agricultural region.

Increased nutrient loads are associated with increased turbidity, and ordinarily increases the oxygen consumption. A good negative correlation (0.93) was found between turbidity (x) and the dissolved oxygen divided by the y, B.O.D., $y = 5.645 - 0.14x$ for the median values of a total of 159 samples at 15 stations along the extent of the Mississippi from 1967 to 1968. When $y = 5.645 - 0.14x$, a turbidity less than 10 p.p.m. is equal to a B.O.D. less than 2.0 p.p.m. In the Mississippi River, the average turbidity at all stations was about 17 p.p.m., and is largely caused by organic matter. When the turbidity is 17 p.p.m. the biochemical oxygen demand (B.O.D.) is about 2.5 p.p.m., and the dissolved oxygen is about 8 p.p.m. When the turbidity is 32 p.p.m. the B.O.D. increases to 8 p.p.m.

Table 11: Annual, seasonal, and range of Turbidity (J.T.U.) in some Minnesota Rivers

River (Location)	Years	Annual		Seasonal Median			
		Median	Range	Winter	Spring	Summer	Fall
St. Louis (Brookston)	1953-1957	14	6 -75	25	16	10	11
	1968-1971	3.9	2.5-36	3.6	7.3	3.6	4.2
St. Croix (Taylors Falls)	1953-1961	9.5	2 -27	7.6	11	11	10
Mississippi (Anoka)	1953-1961	10	1.5-110	7.0	12	20	9
Rum (Anoka)	1953-1961	11	1.6-48	6.5	12	15	9
Cannon (Welch)	1953-1961	14	1.4-220	7.5	18	26	10
Crow (Dayton)	1953-1961	16	3.5-140	9.0	18	28	15
Red (Fargo)	1953-1961	33	3.9-380	12	27	94	27
Minnesota (Shakopee)	1953-1961	35	7 -650	11	45	80	22

Table 12: Amount of Variation in turbidity between seasonal and yearly medians.

River	Seasonal	Yearly
St. Croix	2.4 (7.6-11)	10 (7 - 17)
St. Louis	3.7 (3.6-7.3)	10.5 (3.5-14)
Mississippi	13 (7 - 20)	12 (8 - 20)
Minnesota	69 (11 - 80)	88 (18 - 100)

Water Temperature Characteristics

Temperature changes in creeks and rivers, and the magnitude of the changes are at best poorly understood. In addition to the effect at which biological process occur, the amount of dissolved oxygen present decreases as the water temperature increases. At its saturation point water will contain 14.9 p.p.m. of oxygen at 32°F., 8.5 p.p.m. at 75° F., and 7.2 p.p.m. at 90° F. It's not uncommon for the dissolved oxygen to be as low as 75 percent of saturation, so at 75° F. the dissolved oxygen would be 6.1 p.p.m. Trout need a minimum oxygen concentration of 6 p.p.m. to thrive, so trout occur most commonly at water temperatures 75° F. or lower, but the exact temperature varies between species. Fishes which inhabit water warmer than 75° F. do not require as high an oxygen concentration, but all of them have temperature limitations. Water temperatures are lowest in the winter (32 to 33° F.) and highest from June thru August (54 to 86° F.).

Usually water temperatures have some daily fluctuation and are lowest before sunrise and reach a maximum by late afternoon. The rate at which temperatures increase can vary from stream to stream, by the hour, day, and season, and by soil type. Large bodies of water warm and cool more slowly than smaller ones. At any instant of time, a body of water contains a specific volume of heat, and as time progresses heat is continually being gained and lost at rates that vary. Rather than calculate the volume of heat in calories, it is simpler and more convenient to multiply the stream volume by the temperature to obtain an estimate of the volume of heat. So stream flow (c.f.s.) times the temperature (° F.) equals the volume of heat (c.f.s. degrees). When heat is lost from streams, its radiated upward and downward from its surfaces, and heat is gained from solar radiation and heat radiated from adjacent surroundings.

Since the volume of water present in a waterway is a function of the width, depth, and water velocity, the most convenient way to compare heat losses and temperature fluctuations is to divide the flow (c.f.s.) by the width, and the result will be the flow per foot of width. In the St. Croix River at an ordinary summer flow there is about 4.5 c.f.s. per foot of width, range about 2.9 to 6.7. At the lower end of Cedar Valley Creek in Winona County late in the summer the flow is about 0.5 c.f.s. per foot of width. Then the volume of heat can be measured as cubic foot second degrees per foot of width. At 75 ° F. the volume of heat in the St. Croix would be 337.5 c.f.s. degrees per foot, range - 217.5 to 502.5, and in Cedar Valley Creek 37.5 c.f.s. degrees per foot.

Larger deeper rivers usually have smaller temperature fluctuations than small shallow creeks. In the summer the water temperature over a sandy bottom riffle, there can be a temperature fluctuation of 33° F., from 55 to 85° F., in Cedar Valley Creek. In the St. Croix, the observed fluctuation was 6° F., from 68 to 74° F., at various times of the day, early morning to late afternoon, in June and July. In the St. Croix, the maximum rate at which water warms during the day appears to be about 0.7 degrees per hour, but in Cedar Valley Creek the maximum rate was 3.6 degrees per hour at the lower end in non-trout waters and 2.7 degrees per hour in trout waters. Where the minimum temperature was higher the rate of change was lower, 2.4 in non-trout waters and 1.6 in trout waters. The maximum temperatures observed in non-trout waters varied less than the minimum temperatures.

From the foregoing data, it is possible to calculate how much heat is gained per foot of waterway. In the St. Croix the gain in volume of heat is 27 c.f.s. degrees (6 times 4.5) and the range of the estimate is 17.4 to 40.1 c.f.s. degrees. In Cedar Valley Creek the gain was 10.5 to 15.0 c.f.s. degrees. The gain of heat is ordinarily close to 15 c.f.s. degrees in a day since the St. Croix data was obtained from scattered data which would be the extremes in shallower water. This suggests that narrowing Cedar Valley Creek from 10 to 7 feet, lower end would reduce the temperature fluctuation from 30 to 21 degrees F.

Stream characteristics other than width can modify stream water temperatures. Water at the bottom of pools, that percolates thru gravel riffles at the foot of pools, and that flows from springs is likely to be cooler than stream surface temperatures. Water flowing in from tributaries can also modify a stream's temperature. In Belle Creek in Goodhue County, small springs had water temperatures ranging from 46 to 51^{o} F., water temperatures at the bottom of a pool were 56^{o} F. when the temperature in a riffle above the pool was 60^{o} F., and water percolating out of the gravel at the foot of the bar was 58^{o} F. when the surface water temperature in the pool above the bar was 61^{o} F. A small tributary stream originating in the sand near the main stream had a water temperature of 54^{o} F., and the main stream had an upstream temperature of 66^{o} F. and a downstream temperature of 65^{o} F.

An addition of 3.4 percent of cooler ground water (0.3 c.f.s.) cooled the main stream one degree, so relatively small amounts of ground or spring water can be detected by observing the differences in a surface water profile of a stream. Field estimates of the temperatures and water volume, and missing data can sometimes be filled in by using the formula $V_3T_3 = V_1T_1 + V_2T_2$. In the formula V = volume, T = temperature, the subscript 1 denotes the upstream measurements, 3 denotes downstream, and 2 the tributary. In Bell Creek at the downstream side of the tributary the flow was 9.1 c.f.s.

Caution should be used in comparing air and water temperatures. One day when the air temperature remained relatively constant, 74 to 76^{o} F., the water temperatures near the mouth of the stream increased to 81^{o} F. Another day when the air temperatures increased from 70^{o} F. at 9:30 a.m. to 88^{o} F. at 3:30 p.m., the water temperature only increased to 83^{o} F. which was approximately the same maximum temperature. A stream (Gorman Creek) which was much warmer than Cedar Valley Creek early in the morning also approached a similar maximum temperature 84^{o} F. (figure 15).

EFFECT OF PHYSICAL CONDITIONS ON ORGANISMS

General

Physical stream conditions which are most likely to influence the abundance of plants and animals are the kind substrate, slope of the stream bed, amount of flow, variations in flow, water temperature, and extent of light penetration. Usually the result of the effect of substrate, slope, and amount of flow are measured as width, depth water velocity, and soil particle size. Stable substrates usually produce more plants and animals, and as the force of the water increases soils become less stable, because the size of soil particles which can be moved increases. Silt is stable in water velocities below 0.3 feet per second, sand below a 0.7 to 1.5 feet per second range, gravel below a 3 to 4 feet per second range, and rubble and boulders above 4.0 feet per second. Even where soils are stable, sometimes there are limits to the water force any species of plant and animal can tolerate.

Hynes (1972) presents a classification of water velocities related to plant distributions that seem to have a general practical application, which is as follows: torrential = 70 centimeters or 2.26 feet per second, non-silted = 25-70 centimeters or 0.82-1.96 feet per second, partly silted = less than 10 centimeters or 0.31 feet per second. Note that the velocities of many of the larger rivers fall into the non-silted range where sandy soils can readily erode.

To exist in flowing water, a fish needs shelter from the current to rest in, even though they can swim fairly fast for short periods of time. Hynes (1972) notes the following about the swimming ability of fish: "Fishes accumulate lactic acid in their tissues very rapidly so they tire easily. They actually accumulate lactic acid three to eight times as fast as mammals and take six to twelve times as long to get rid of it. They thus need shelter fairly often, even though they can swim well in short bursts. Bainbridge discovered, to his surprise, that goldfish could keep swimming for longer than either the dace Leuciscus or trout, but perhaps this merely reflects the differences of the way of life of these species."

Body muscles use glycogen under anaerobic conditions, during rapid contraction which is reduced to lactic acid. Lactic acid accumulates until it is reduced by oxygen into carbon dioxide and water, or is resynthesized into carbohydrate. Apparently, fishes differ in their rates of accumulation and reduction of lactic acids. So the rates at which these various processes occur accounts for the various habitat requirements of fish.

Generally, higher aquatic plants are restricted to water velocities less than 2.3 feet per second, while algae and moss grow well at higher velocities their numbers are restricted. Some plants and animals only grow well when there is sufficient current to supply nutrients and/or oxygen, but all require stable bottoms.

To develop optimum communities, some plants and animals require specific kinds of substrate. Other plants and animals are at least reasonably abundant on many kinds of substrate, but tolerate marginal conditions better than others.

Water flowing over substrates rich in lime (Calcium carbonate) produces more invertebrates, benthos, than substrate with much less lime. Carlander (1955) notes that the total alkalinity in reservoirs accounted for 69 percent of the variation in the standing crops of fish in reservoirs, but in trout lakes it was only 28 percent of the variation. Moyle (1952) notes that each of the geologic regions in Minnesota have a different type of water fertility which is related to the type of rock or glacial deposit. He also notes that nitrogen, phosphorous, and alkalinity of the water tends to increase as the total dissolved solids increase. He also notes that fish crops were noted to increase as the total alkalinity increases, but there were variations from that trend. Streams flowing over igneous rocks in northeastern have a much lower total alkalinity than streams flowing over limestone and dolomite in southeastern Minnesota. In 1974 the total alkalinity in the North Shore streams was 38 p.p.m., and 272 p.p.m. in the Whitewater River in southeastern Minnesota.

Making a general statement about the effect of temperature on biological systems is somewhat hazardous, but Tarzwell's observations can be expanded to illustrate what could happen to standing crops of organisms as temperatures decrease. To do this one must assume that optimum temperature for development is over 70° F., and that the rate of decrease of the standing crop is the same in the range of temperatures to be investigated 32 to 72° F. Tarzwell noted that the standing crop was 65 to 77 (ave. 71) percent of maximum when the temperature was 10° F. lower. So if the standing crop is 1.0 at 72° F., the standing crop would be 0.71 at 62° F., 0.51 at 52° F., 0.36 at 42° F., and 0.26 at 32° F. So the standing crop at 32° F. would be 26 percent of the standing crop at 72° F. These figures should be considered an illustration only. Moyle's 1947 figures for the St. Louis River Basin are somewhat larger. The decrease (about 49 percent) in the standing crop (volume) of benthos from warm water streams to coldwater streams, but the number of organisms present was the same. The average temperature difference was about 8 degrees from 60° F. to 68° F. in these samples.

AQUATIC PLANTS AND PHYSICAL LIMITATIONS

Kinds Present

Since higher aquatic plants are likely to be absent when water velocities are high, the kinds of algae found to occur commonly in Minnesota's rivers and streams was tabulated from the early surveys of the Mississippi, St. Louis, Root River System, and the streams tributary to Lake Superior. The genera of algae occurring commonly in more than one river system are as follows: Diatoms-Cymbella, Fragilaria, Melosira, Navicula, Surirella, Tabellaria, Synedra, and Cymatopleura. Desmids - Pediastrum, Closterium, and Cosmarium. Bluegreen Algae - Anabaena, Coelosphaerium, Microcystis, and Oscillatoria. Green Algae - Cladophora, Spirogyra, Oedogonium. In any river system while 40 or more genera of algae might be present, only 10 or 15 might occur commonly.

Except below lakes that might have large concentrations of algae, the species which occur most commonly are attached to a firm substrate. Some species are motile and occur more commonly where currents are not high. Sometimes long strands of algae can be observed waving in the current, others occur as relatively thin slippery films (diatoms) or mats on rocks or other firm substrate. In the Mississippi system river plankton samples, there were about 200 diatoms, 200 green algae and desmids per liter, and about 70 bluegreen algae per liter. Below lakes with large concentrations of bluegreen algae, the concentrations ranged from 2 to 14.4 thousand per liter. About 500 per ml. can be considered a bloom (Mackenthun (1965). Except for some bluegreen algae, these are algae which have come loose from the substrate. Only one of five Rivers had only large amount of plankton in it. The Elk River had 167 per ml. mostly bluegreen algae.

Mosses (Bryophytes) appear to be restricted to rocks and sticks in smaller streams where they are occasionally found. About the St. Louis System, Moyle (1947) presents the following summary: "In the smaller headwater streams, lichens and mosses are common on rocks, and in deeper water of such streams water mosses of the genus *Fontinalis* are sometimes abundant." In the southeast the moss *Amblystagium fluviatile* occurs commonly on submerged rocks in the clearer spring fed streams and is aboundant in springs. There is some indication that they require a fairly high concentration of nitrate nitrogen.

Many species of aquatic plants occur in or along the margins of streams, but most of them are associated with quiet waters such as pools, backwaters, or where lake-like conditions exist. Moyle notes that there are about 175 species of plants that are more or less aquatic, and only about 40 or 50 percent of them might occur in a river and stream. Where average water velocities are fast enough to be non-silting, only about 10 percent of them are likely to occur in or along a stream's margin. In the faster waters of a stream the submerged aquatics most likely to occur are wild celery, river pondweed, sago pondweed, white buttercup, claspingleaf pondweed and mud plantain, and of these, river pondweed and wild celery are likely to occur in fairly dense beds. Along the margin of rapidly flowing streams in the quiet water, wild rice, arrowhead, burreed, bulrush and cattails are the commonest emergents, duckweeds frequently collect in the emergents. Plants such as horsetail and watercress are frequently associated with springs and seepage into rivers. Water moss, watercress and white water buttercup also appear to be associated with water with a high nitrate content, which is frequently characteristic of spring water.

Effects of Physical Conditions

Streams with shifting sand bottoms caused by high water velocities have few or no plants, but where ordinary maximum surface velocities are less than 0.8 feet per second and bottoms are primarily sandy, good stands of submerged aquatic plants are likely to be present. In the Upper St. Croix River a shifting sand bottom (water velocity 1.5 to 2.0 feet per second) was stabilized in localized areas with brush and logs. A year after installation a midstream brush shelter had a good stand of river pondweed behind it. Brush and logs extending from the shore had small stands of Canada water weed growing downstream in the quiet water. Log structures that dug holes in the bottom had no plants growing near them. Midstream brush cover was difficult to anchor in shifting sand.

In rivers where water velocities are low and bottom soils are stable, several species of aquatic plants are likely to occur. For example, 13 species of submerged aquatic plants were present in the upper Mississippi River where water velocities were less than 0.8 feet per second, but were absent where water velocities were more than 2.3 feet per second. Rather than being a species shift as water velocities increase, plant abundance and number of species decreased as water velocities increased. No plants were found on unstable bottoms, but some of the 13 species were able to exist on stable bottoms where maximum water velocities were between 0.8 and 2.2 feet per second.

At water velocities less than 0.5 feet per second, submerged plants grew across the channel on sandy bottoms and were restricted to the rivers edge at water velocities up to 1.5 feet per second on sandy bottoms. At velocities from 1.5 to 2.3 feet per second, a couple of species were found on coarse soils (gravel) along the water's edge. Hynes (1973) showed a similar relationship for European species, none of which were found at water velocities above 2.3 feet per second, 21 percent were found at 0.8 to 2.3 feet per second, and 93 percent below 0.8 feet per second.

Tarzwell's data indicated that the largest number of invertebrates were produced where plants such as Canada waterweed and wild celery are present, the next largest number where moss was present, the next where coarse soils of non-eroding soils were present, and the lowest number on easily eroded sandy soils.

Few or no aquatic plants are found in turbid streams, and are abundant in clear fertile streams with firm substrates. Except below lakes with heavy plankton blooms, most of the turbidity is usually caused by organic materials - stain or small plant particles. To effectively utilize the nutrients present in rivers and streams, they must be clear enough to allow submerged aquatic plant growth. Except in some reservoirs, the main difference between lakes and flowing waters is that fast flowing streams and rivers do not develop intense algae blooms.

In small reservoirs, water is not retained long enough to develop a plankton community. In the impoundment at Taylor's Falls, at ordinary river flows, water is not retained long enough to develop a plankton population. The flow-through time is about 1.7 days at the average flow of 4000 c.f.s. Sometimes, later in the summer at low flow, noticeable amounts of algae are present in the water. At a flow of less than 1500 c.f.s., the flow-through time is more than 4.7 days, which allows sufficient time to develop a noticeable algae population.

When reservoirs and river lakes are very long, they are clearest at the lower end and most turbid near the upper end. When the turbidity is more than 8.0 p.p.m. at the head of Lake St. Croix, the turbidity is 7.5 p.p.m. at the foot of the lake, 22 miles downstream. Generally the lake is clearest at low flow, but at times the water is delayed sufficiently so that noticeable amounts of plankton can be observed in the lower end of the lake.

Whether submerged aquatic plants grow in lakes or streams, light is necessary for their growth. Peterson (1973) presents data that shows that all of the species of submerged aquatic plants were present, and occurred over 98 percent of shallow lake bottoms when the secchi disc water transparency of 3.5 feet of the species, occurred on 50 percent of bottom at 1.0 foot transparency, and this was mostly one species, sago pondweed. Only sago pondweed was found on 5 percent of the bottom at any 0.5 foot transparency. Sometimes emergents such as cattails were present in dense stands along the shoreline in lakes, but in rivers cattails are only observed where the shoreline of a stream is low and marshy.

Since most pools are likely to be deeper than three feet, a turbidity less than 7.0 p.p.m. is needed. At an average turbidity of 7.0 p.p.m., the secchi disc water transparency is about 3.7 feet, at 10 p.p.m. the transparency is about 2.6 feet, and 1.0 foot at 25 p.p.m.

INVERTEBRATES

Kinds Present

Since data on composition of invertebrate populations in rivers and streams is available from a large series of samples in eastern Minnesota, they were summarized to obtain an average invertebrate composition of running waters. Insects comprise about 78 percent of the invertebrates in an ordinary sample, and 22 percent crustaceans, clams, snails aquatic worms, and leeches, which are ordinarily 8, 5, 5, 2 and 1 percent of a sample, respectively. Three groups of insects usually comprise 74 percent of the total sample, diptera (usually midges) 44 percent, mayflies 17 percent of the total sample. (See Figures 10 and 11 for the numbers found in the various river systems, note that the numbers of the various groups vary considerably between the various river system.

Species compositions can vary considerably on various substrates. Hynes (1973) shows that, on sand and muck bottoms, midges were 83.9 and 74.8 percent respectively and mayflies were 9.3 and 20.3 percent of the population, respectively. On rubble and gravel bottoms, midges were 38.2 and 67.6 percent of the population respectively, and mayflies were 35.5 and 4.6 percent of the population respectively. Insect emergence was 4.6 and 1.8 times higher on rubble rapids and muck bottoms respectively than it is on sand. Midges are most abundant on muck bottoms and their density tends to decrease as soil particle size increases. Other insects are most abundant on stable soils (rubble and muck) and least abundant on unstable sand (see figure 12).

Use by Fish

Since fish are usually concentrated in pools, it seems the benthic standing crop should be lower in pools and higher in rapids where fish are basent. Hayne (1956) shows that benthic standing crops are higher where fish are absent. Since fish can graze invertebrates to low levels, it is sometimes necessary to know how fast the population is turning over to determine the amount of food available. Waters (1969) states that in the information available the turn-over ratio of invertebrate populations ranges from 2 to 5 (mode about 3.5). Invertebrate populations on muck bottoms are quite variable. While they can be relatively high, some data shows them low. Bottoms that are subject to scour by floods are likely to have low populations of fish and benthos. Fish and benthos are most abundant where soils are stable, and in the St. Croix they were most abundant on rubble soils and least abundant on midriver sandy soils (Figures 4 and 9).

Hunt (1965) notes that surface drift insects are an important source of food of trout, and he also summarizes the literature where he notes that some minnows and darters use surface drift as a source of food. Suckers and sculpins do not. He notes that mayflies and Diptera (true flies) are 52 and 22 percent of the surface drift insects, and were 65 and 11 percent of the food consumed by trout.

In warm water streams smallmouth bass less than six inches in length feed on drifting organisms, fish fry, insects, and cladocerans. Large crustaceans, large land insects, and fish are the primary constituents of the diet of larger smallmouth bass. Table 13 shows the results of the analysis of 160 smallmouth bass stomachs in the Kettle River System in 1954 and 1956. In the Kettle River, only 0.2 percent of the northern pike diet was composed of insects. Fish were 80 percent of the diet (primarily minnows), and the remainder was crayfish, frogs, and mice. Walleyes feed extensively on invertebrates at times (Johnson 1969), but when fish are available they utilize them.

Table 13: Food in 160 smallmouth bass stomachs and percent of total volume in various sized fish in the Kettle River System in 1954 and 1956.

Type of Food	Percent by Size Groups (inches)					
	0.5-0.9	7.0-1.9	2.0-3.9	4.0-5.9	6.0-9.9	10.0-15.0
Fish	65	15	2	14	26	12
Crayfish	0	0	0	34	72	77
Small Crustaceans	0	14	Tr.	0	0	0
Insects	34	71	98	50	1	11
Mayflies	--	--	72	23	1	0
Dragonflies	--	--	8	8	0	3
Stoneflies	--	--	6	3	0	0
Beatles	--	--	6	3	0	0
Back swimmers	--	--	2	0	0	0
Other	--	--	4	4	0	0
Land Insects	--	--	0	0	0	7
Unidentified	1	0	0	2	1	0
Stomachs Examined	18	19	55	33	35	20
Month-Year	6-56	7,8-56	7,8-54	7,8-54	7,8-54	7,8-54

Effects of Physical Conditions

Observed standing crops vary from about 0.05 to 3.00 ml. per square foot with the median being 0.80 ml. On fine textured soils subject to erosion, standing crops are usually below 0.30 ml. per square foot; around 0.05 to 0.09 ml. on shifting sand and 0.20 to 0.30 ml. on clay and coarser on more stable sands. On ledgerock the standing crop in flowing water is usually about 0.40 to 0.50 ml. per square foot. On rubble boulder bottoms standing crops are ordinarily about 1.5 times above average. On stable soils where plants are present, standing crops are usually higher than 1.2 ml. per square foot. On mucky soils, which only occur where the current is very low (below 0.3 feet per second), standing crops of invertebrates are usually above average. In an average sample there are about 250 to 450 organisms per ml., so there are usually 200 to 360 (mean = 280) organisms in an average sample. These figures exclude large clams.

Standing crops of benthos are governed by the stability and type of substrate, and permanence and force of water. Standing crops of benthos were highest on rubble substrates which are most resistant to the force of water, and lowest on shifting sand substrates which are easily eroded at ordinary water velocities. Where plants are present, water velocities are low, and the substrate is stable, standing crops of benthos are high. Even rocky substrates do not withstand severe flash floods--for example, on Crooked Creek after a flash flood the standing crop was about three percent of the ordinary standing crop in adjacent streams. Tarzwell (1937) states that, in frequently flooded streams, standing crops were ordinarily 12 to 24 percent lower than standing crops in stable streams. In the zone of fluctuation in reservoirs, standing crops are about 25 percent of the crops where water levels are stable. Channeling decreases standing crops of benthos about 85 percent (Morris, 1968).

In the impounded waters from Brainerd to the Twin Cities, stable soils should produce an above average standing crop of invertebrates, but they were only a quarter of the volume and a third of the average standing crop present in the river. Moyle (1940) notes that in Mississippi River impounded waters from Brainerd to the Twin Cities 98 organisms with an average volume of 0.22 ml. per square foot were present. In non-impounded water, 277 invertebrates per square foot having a volume of 0.90 ml. were present, nearly average numbers and volume. Background data about Leech and Winnibigoshish Headwaters Reservoirs show that, at a depth of one foot within the zone of fluctuation, the standing crop was less than 15 percent of the standing crop at 4 to 13 feet (see figure 2).

Data from a hydroelectric impoundment on the St. Croix River shows similar variations (see figure 5), and includes data on the river below the impoundment. On rubble bottoms, in the impoundment the number of invertebrates (benthos) in water 2 to 3 feet deep was one third of the number above the impoundment. Downstream from the impoundment almost no benthos was found on rubble bottoms in water two feet deep. Figure 3 shows the crops of invertebrates above, in, and below the impoundment and also illustrates why the impoundment populations were low. Apparently water level fluctuations were the cause of the low benthos densities.

FISH AND EFFECTS OF PHYSICAL CONDITION

General

When some species lists for various sized streams were compiled, it became apparent that most warmwater species were present to some extent in streams and rivers of various sizes, that the coldest streams had fewer and frequently different species of fish, that some warmwater fishes were present in coldwater streams, that larger sized fishes dominate the fish populations of larger rivers, and that small fishes, such as minnows, were likely to be most abundant in small streams.

Table 14: Percent composition of the fish populations by weight in various kinds4/ of Minnesota waters.

Category of fish	Centrarchid Lakes	Rough fish Lakes	Rivers1/	Southeastern Streams	North Shore trout waters
Game fishes	12.0	3.2	9.0	12.8	65.1
Sport fishes	38.6	16.0	0.6	0.03/	0.0
All rough fish	28.0	80.0	90.4	67.9	11.8
Catastomids - carp	8.0	69.0	90.1	67.9	10.3
Others	20.0	11.8	0.3	0.0	1.5
Small fishes	21.4	7.4	trace	29.4	18.2

1/ Average yearly flow over 100 cfs. 2/ Mostly trout streams.

3/ Ordinarily 4 percent or less in warmwater streams.

4/ The kinds of fish arranged in broad species groups which are as follows: large rough fish (suckers, redhorse, carp suckers, buffalo, and carp), game fishes (smallmouth bass, walleye, sauger, northern pike, channel catfish, trout, and white bass), sport fishes (centrarchids, except smallmouth and largemouth bass), small fishes (minnows, mudminnows, darters, trout perch, sculpins, and brook stickleback), and other fishes (ordinarily bullheads and yellow perch, and occasionally drum, gar, burbot, dogfish, and sturgeon).

Since species of fish tend to be arranged according to temperature and size of stream, the following lists were prepared to illustrate what species might occur in various kinds of streams.

Coldwater Streams

In coldwater streams, the fish which occur commonly are trout (rainbow, brook and/or brown trout), sculpins, blacknose dace, and white suckers with parl dace and creek chubs. Johnny darters occur more commonly in the warmer coldwater streams and white suckers occur least commonly in the coldest streams. Very cold portions of streams might be predominantly trout.

Warmwater Streams and Rivers

Small warmwater streams less than 20 feet wide are frequently inhabited by small sized fishes. Species such as creek chubs, johnny darters, common shiners, blacknose dace, longnose dace, redbelly dace, fathead minnows, bluntnose minnows, brassy minnows, mudminnows, and yellow perch occur frequently. Larger sized species are ordinarily white suckers, northern pike, and sometimes burbot and smallmouth bass.

In small rivers and streams from 20 to 40 feet wide, fish which occur are northern pike, smallmouth bass, rock bass, white suckers, hog suckers, blacknose dace, longnose dace, common shiner, spotfin shiner johnny darter, yellow perch, black bullhead, burbot, and stonecats.

In intermediate sized rivers from 40 to 100 feet wide, fish which commonly are found are northern pike, walleye, smallmouth bass, channel catfish, white sucker, redhorse, quillback, carp, hog sucker, white bass, rock bass, stonecat, and black bullhead. To a lesser extent, small fishes such as longnose dace, blacknose dace, common shiner, spotfin, and johnny darters are present.

In rivers wider than 100 feet, minnows are present, but not very abundant. Johnny darters, log perch, madtoms, and trout perch might be fairly abundant, but the main species of fish are northern pike, walleye, channel catfish, smallmouth bass, redhorse, white sucker, buffalo, carp, sheepshead, hog sucker, white bass, carp suckers, dogfish, bullheads, and sturgeon.

There are two general groups and subgroups of spawners found in rivers. There are those which spawn on suitable substrate in the main channel. Each of these groups can be divided into nest builders which give some parental care to eggs and fry and "random" spawners. Northern pike, catastomids, and the percidae are random spawners. Nest builders include the Centrarchids and Ictaturids. Apparently, the Cyprinidae include both nest builders, minnows, and random spawners carp. When water levels do not raise sufficiently and remain reasonably high long enough, few young-of-the-year fish are produced by species which depend on shallow water adjacent to the main channel for spawning. Excessive water velocities, a rapidly falling water level, and poor substrate are the principal causes of poor spawning success in the main channel. Eggs of random spawners are swept downstream after severe storms by excessive water velocities and get buried and/or damaged, and this can cause a reproductive failure in random spawners. While nest builders such as smallmouth bass have the same problems, they will renest with some success if the loss occurs early in the season. Rapidly falling water river levels have been known to strand smallmouth bass nests.

Water stages, longterm, annual, and short term, can have an effect on fish production including success, either directly by stranding and flash flooding or indirectly by reducing the food supply. All these problems can be divided into acute and chronic events. One common chronic problem is that oxbows and shallow lakes become isolated from the main channel and winterkill as main channel water levels recede. These shallow lakes and oxbows will sustain fish life if there is sufficient inflowing oxygenated water. An example of an acute problem is when an occasional flash flood scoures a stream and reduces production temporarily, and the stream recovers from the effects rapidly. Over a long period of time chronic problems are usually the cause of the greatest loss of production. For example, if both channeling and a flash flood reduce organisms density 85 percent, and the flash flood occurs every ten years, over a ten year period the channeling will reduce the population density an average of 85 percent per year, but the flash flood will only reduce the population density an average of one tenth of 85 percent on 8.5 percent per year.

Measurements and Effect of Stress

The average diversity index (a measure of population quality) for Minnesota's warm water streams varies from 1.8 to 2.6 (average 2.2), and is much less where considerable environmental stress is present (Peterson, 1975). The diversity index can vary from one part of the river to another, so values calculated from several miles of electrofishing are average values. For example, the average diversity index for the Snake River was 2.71 (range 1.39 to 2.97). Slightly lower than average values (2.27 to 2.36) were characteristic of the steeper gradient rocky bottoms (over 4.0 feet per mile).

Unstable (eroding) soils create enough environment stress so that the diversity index was low (0.45 to 0.96 in the St. Croix), and most of the fish population is composed of rough fish. In contrast, the diversity index was fairly high (2.65) in a St. Croix River rapids where rocks predominate, and large rough fish were only 35 percent of the fish population. Where stream bottoms are mostly stabilized sand, Upper Mississippi below Winnibigoshish Reservoir, the diversity index was 2.09. In the Mississippi River near Monticello, where rocky gravel bottoms are likely to prevail, the diversity index was about 1.85.

As water velocities increase the diversity of fish decreases. From stratified samples from the Upper Mississippi Rivers and St. Croix Rivers, it was noted that the equation $Y = 2.82 - 1.26 X$ summarized the results of the samples from various types of habitats fairly well. In the equation, Y is the diversity index and X is the surface water velocity expressed in feet per second. Where the stress from water velocity is zero, the diversity index ranges from 2.55 to 3.15, and where a diversity index of zero is caused by the force of water, the water velocity is 2.26 feet per second. At any average diversity index of 2.23, the water velocity is about 0.5 feet per second, the velocity in pools.

It appears that there are three distinct stress problems associated with the force of water (measured here as velocity) on the aquatic environment, and these are the stability of the substrate, the kind of substrate and attachments, and the ability of the organisms to wishstand the force of the water. In the foregoing equation where $Y = 0$, the water velocity was 2.25 feet per second. This suggests that a fish ordinarily does not tolerate water velocities higher than that.

All of the following test values indicate that the calculated value of 2.26 feet per second is a reasonable statement about the cruising speed of larger fish, but it also indicates that the cruising speed increases as size increases. Clay (1961) summarized a considerable amount of data on the ability of fish to swim against various water velocities, and notes that six inch trout, dace, and goldfish could swim for one second against a water velocity of 5.4 feet per second and also notes that chinook salmon 1.5 inches long could swim against a velocity of 1.0 feet per second for ten minutes and striped bass three inches long could swim against a velocity of 2.0 feet per second for 10 minutes. Salmon fry have a cruising speed of 0.5 feet per second. The formula $V = A\ (1.23\ L - 1)$ will predict the cruising speed at 70° F., V = cruising speed, L - length in inches, $A = 0.4$. In cold water, V decreases 50 percent. In any event, the formula is tentative.

In any smaller, clear river with good quality habitat, the depth of water at any specific point has a considerable effect on species diversity, numbers, and sizes of fish caught. Riffles were largely inhabitated by small and immature fish, shallow pools had a 50-50 combination of immature and adult fish, and deep pools were largely inhabited by adult fish. In the Mississippi River below Winnibigoshish lake the following data was collected. In riffles, the maximum depth ranged from 1.0 to 3.0 feet, water velocities ranged from 1.0 to 2.4 feet per second, and the diversity index ranged from 1.10 to 1.58. The catch was 79.5 percent immature fish, and the catch per hour ranged from 167 to 309. In shallow pools the depth ranged from 3 to 6 feet, water velocities ranged from 0.3 to 0.9 feet per second, and the diversity index ranged from 1.98 to 2.26. In shallow pools the catch was 55.5 percent immature fish, and the catch per hour ranged from 97 to 152 fish. In deep pools the maximum depth ranged from 6 to 8 feet, water velocities ranged from 0.3 to 0.9 feet per second, and the diversity index ranged from 2.00 to 2.45. In deep pools the catch was 10.5 percent immature fish, and the catch per hour ranged from 37 to 69 fish.

In any larger river with high water velocities such as the Upper St. Croix, the best fish habitat is associated with pools below rocky rapids, along rocky shorelines, or frequently outside river bends. Few fish except sturgeon are present in sandy midstream reaches with high water velocities. Along sandy shorelines the density of fish is about one fifth of the density along the productive shoreline. Where the productive shoreline is absent as in straight reaches, the overall catch, two sandy edges and the center, the density of fish would be 55 percent lower than maximum providing overhanging trees and snags are present. If cover is not present, then the density of fish would be 89 percent lower than maximum, three times the midstream density divided by the sum of the densities in table 16 b.

Where a productive shoreline is present the catch per hour would be 87.5, along less productive sandy shores with cover, the catch per hour would be 32.3, along bare sand reaches the catch per hour would be 8. Where two productive shores are present the average catch per hour would be 112.7. In the foregoing water velocities were 1.6 feet per second or higher near the shore and the principal aquatic plants were river pondweed and water celery on stable bottoms.

Variations in water flow can have a profound effect on the standing crop of fish by eliminating cover food, interfering with spawning and standing, and killing fish. Hiner (1947) shows that the standing crop of fish on Crooked Creek was 26 percent of the standing crop in an average Root River System Trout stream after a flash flood and the benthos was about 2 percent of the normal level in Root River Streams. This absence of benthos caused trout to shift to a diet of earthworms. Frequent variations in water levels reduce the standing crop of benthos, so the standing crop of fish is lower. (Figure 6).

Effects of Alterations

Many streams have poor bottoms and are too shallow to contain good populations of catchable sized fish, so it seems reasonable that if more deep water, cover, and good substrate were created that the biomass and numbers of larger fish would increase. Hunt's (1971) data shows that when the mean depth was increased 40 percent the pool area increased 289 percent. He also shows that after stream improvement there was a positive correlation between the number of trout longer than six inches and the number of feet of bank cover and square feet of pool area. No correlation was found between the number of fish smaller than 6 inches, and bank cover and pool area.

In Minnesota, Hale's (1969) work showed similar results for stream improvement on the Split Rock River. There was an increase in average depth, bank cover, pool area, standing crop, and angler harvest after stream improvement. The general approach to stream improvement has been ti narrow and deflect the stream's current so that the current will clean out the fine particles (sand) and provide deeper water in the constructed bank cover.

If a stream is made shallower and wider by channeling, the number of large game fish should decrease, the fish population should be dominated by small fish, and the standing crop of fish should decrease. On fine textured soils (sand) this was what happened on the Roseau River. The effect of channeling was still present 60 years after the river had been modified. Even though the gravel bottom part of the stream had been channeled, the standing crop of larger fish was at least occasionally high, but the game fish population was dominated by small fish.

In the Roseau River it was determined that there was a direct correlation ($r = 0.76$) between the diversity index and the hydraulic radius of the river where the samples were taken. The equation $Y = 1.0 + 0.45X$ express the relationship between the diversity index and the hydraulic radius where X = hydraulic radius. (approximates average depth) and Y = the diversity index. Where the diversity index was low the river was relatively wide and shallow. The portions of the stream with the lowest diversity index had been extensively channeled and were wide and shallow. Over gravel and rubble bottoms the diversity index was 1.13 times higher than the equation indicated and over sand bottoms the index was 68 percent of the value indicated by the equation. Table 15 summarizes some of the data by stream sector. Where trees had fallen into the river, cover was provided for fish and the diversity index was high.

The part of the river with the sand-silt soils and with fallen trees as cover had the highest diversity index (3.08). The density of the "adult" game fish population in the channeled portion (diversity index 1.31) was 81 percent lower than in the unimpounded portion with fallen trees for cover. While the diversity index was highest where fallen trees provided cover, the density of "adult" fish on natural rubble-boulder bottoms was four times higher. There also was a 1:1 distribution between immature and adult fish over rubble boulder bottoms. On gravel bottoms there were four immature fish for every adult, and the diversity index was low (1.89).

Catches of large sized game fish were lowest on the sand bottomed channeled portion of the river, highest on the coarse textured soils with natural and channeled bottoms, and intermediate over sandy-silt bottoms. There was direct relationship between the diversity index and the percent of adults in the populations (see tables 16 and 17). The percentage of adults was highest where the diversity index was highest, and low where it was lowest.

Table 15 - Diversity, composition, and numbers of fish found in various kinds of habitat as determined by depth, water velocity, and substrate.

Habitat	Maximum water velocity Ft./sec.	Depth (ft.)	Diversity Index	Aquatic Plants (Pct)	Soil Type	Catch per Hour	Percent Composition			
							Game fish	Sport fish	Large rough fish	Other fish
River Channel Edge	1.7	(3-6)	0.45		sand	44	4	0	94	2
River Channel Edge	1.7	(3-6)	0.97		gravel	165	5	1	92	2
Riffles	1.0-1.4	(1-3)	1.10		sand	167	2	14	0	84
Riffles	1.0-1.4	(1-3)	1.58		sand-gravel	309	4	3	34	63
Shallow pools	0.3-0.9	(3-6)	1.98		sand	97	12	13	15	63
Shallow pools	0.3-0.9	(3-6)	2.26		sand	152	10	21	12	60
Deep pools	0.3-0.9	(6-8)	2.00		sand	69	6	7	45	42
Deep pools	0.3-0.9	(6-8)	2.45		sand	37	40	4	17	39

Table 16 a - Physical characteristics of the various parts of the Roseau River associated with the diversity index of the fish population.

Diversity Index	Hydraulic Radius	Stream Modification	Dominant Soil Type	Cover
3.15	3.45	Impounded	100% sand & silt	fallen trees
3.08	5.12	40% dredged	100% sand & silt	fallen trees
2.51	2.75	none	45% rubble	aquatic plants & boulders
2.05	1.82	100% dredged	50% gravel	none
1.31	2.04	80% dredged	80% sand	none

Table 16 b - Catches of fish across the St. Croix River in two hours of electrofishing in each of three strata, best river edges midstream, and poorest edge.

	River Edge, Aquatic Plants Gravel-Rubble	Midstream, Sand	River Edge, Sand	Total
Redhorse/Hog suckers Quillback	297 (90)	8 (50)	85 (95)	390 (90)
Ch. Catfish, S.M.Bass	15 (5)	0	1 (1)	16 (4)
Bluegill, R. Bass	2 (tr.)	0	0	2 (tr.)
Darters	8 (2)	0	2 (3)	10 (2)
Lamprey	7 (2)	2 (12)	0	9 (2)
R. Sturgeon	1 (tr.)	6 (38)	1 (1)	8 (2)
Total Catch	330	16	89	435
No./Hr.	165	8	44.5	87.33

Table 17 - Computation of the density of game fish present in various parts of the Roseau River and the associated diversity index and substrate.

Location	Catch Per Hour	Percent Game Fish	Game Fish Per Hour	Percent Large Game Fish	Catch Large Game Fish Per Hour	Diversity Index (d)	Dominent Soil Type	
							Kind	Pct.
Impoundment	119	2.1	32.2	54.3	17.4	3.15	sand-silt	100
Nr. Lake Roseau	88	17.7	15.6	73.5	11.5	3.08	sand-silt	100
Big Swamp	156	72.8	113.5	1.9	2.2	1.31	sand	80
Above Caribou	459	50.4	272.6	25.6	69.7	2.05	gravel	50
Nr. Caribou	150	50.5	75.8	61.5	46.6	2.51	rubble	45

Discussion and Summary

While aquatic flora and fauna appear to be fairly well adjusted to normal annual and daily changes in a good quality environment, optimum standing crops are considerably lower where more extreme conditions occur. In all the data that was examined, high densities of fish were associated with high densities of benthos and low densities were associated with a variety of unfavorable conditions. All factors affecting crops must be identified and evaluated before final conclusions about the cause of low productivity can be determined.

Unproductive situations in streams can be caused by any of several physical conditions. Aquatic plants do not occur where water velocities are more than 2.2 feet per second, and where aquatic plants are absent, a physical problem other than water velocity is present. The most extreme conditions which might be observed and that reduce and/or overall fish and benthos crops 70 percent or more below optimum are (1) flash floods, (2) unstable fine soils associated with highwater velocities, (3) excessive turbidity which might be related to eroding river banks or run-off, and (4) excessive changes in water stage along the productive shore zone during the active growing season (June, July and August). Fluctuating water levels eliminate both plants and benthos so the amount of aquatic plants present indicate the effect of water level fluctuations on standing crops or organisms.

The example in figure one shows the effect on invertebrate densities in shallow water where aquatic plants are absent, water is impounded, not impounded, and transparency is relatively high and low. The standing crop of benthos was 66 percent below optimum in the Mississippi River where plants were absent, and the shore zone population was 70 percent below optimum in a reservoir. Optimum standing crops of larger fish are not produced when the area is too shallow, too deep, lacks cover, or lacks food.

Much of the years biological production in waterways takes place from late spring to late summer when water stages are likely to be decreasing so exposure of productive bottoms is likely to occur. In the spring high water velocities associated with the higher flows cause stream bed erosion and losses of aquatic organisms. Severe summer storms have the same effect. Ordinarily, flows are highest in the spring, lowest in late winter and late summer, and intermediate in the fall. There are two ways the effects of high flows can be moderated (1) by increasing the size (width) of the waterway (2) impounding and releasing water slowly. Low flows or decreasing flows can be adjusted somewhat by releases from reservoirs, but releases are always limited by the reservoir storage capacity.

Concentrations of organisms are highest in well illuminated water where aquatic plant life is present. Aquatic plants provide shelter and food for animals. Whenever light penetration decreases, sometimes with decreasing river stages, the standing crop of benthos decreases, and this decrease is usually associated with unstable waterway soils or turbid drainage from adjacent lands, lakes, or ponds. Generally, rivers without bog stain in forested regions are clearest in the summer and midwinter and most turbid in the spring. In the agricultural region rivers are clearest midwinter, most turbid midsummer, and in an intermediate condition in the spring and fall. High summer water turbidities are frequently associated with intensively used lands and eroding stream beds and banks. High water velocities caused by severe summer storms and the spring snow melt erode waterway banks and beds and are sources of turbid water.

Water velocities tend to be highest in the center or deepest part of a waterway, so standing crops of organisms tend to be highest along waterway where velocities are low margins, or where the water is shallow and bottoms are rocky. Relatively small changes in light penetration and water stage can reduce the size of the standing crop of organisms present substantially when high turbidities limit aquatic plants to a streams margin. The productive area in shallow rocky riffles and rapids extends across the waterway, so the effect of small changes in summer water stage and light penetration on standing crops is less extreme. Rubble bottoms are mor productive because they are most stable and there are more spaces between the rocks that provide shelter for organisms. Bedrock provides a stable bottom, but there are fewer organisms present, because there are no spaces between the rocks for them to live in.

Warmer waters are more productive, volume of organisms per unit of area, than colder water and different species of organisms are likely to be present in cold waters. Tarzwell's data shows the standing crop of trout streams to be 29 percent lower where the temperatures are 10° F. colder. Since there is a difference of 14° F. (range 58 to 72) in the June, July, August average air temperatures in Minnesota, the standing crops in the coldest part of Minnesota can be expected to be more than 29 percent lower than in the warmest part of the state. Streams in the same watershed can vary considerably - for example, in the St. Louis River watershed coldwater streams, the standing crops were 49 percent lower than the volume found in warmwater streams, but the number or organisms present was the same.

Nutrients are derived from soils in a stream's watershed, so the basic fertility of the soils, including rocks, determines the fertility of the stream. Standing crops of benthos in riffles are twice as high where limestone predominates and the waters total alkalinity is high as contrasted to where granite predominates, and the tital alkalinity of the water is low. This relationship is also well documented for lakes. Differences in nutrient supply can cause the numbers of organisms to vary considerably from one location to another in a stream. This is obvious in classic cases of pollutions, but is not obvious where nutrient supplies change naturally.

When two extreme conditions such as light penetration and water level fluctuations are restricting crops, the primary limiting physical factor lowers the crop an initial amount and the secondary lowers the crop in additional amount from the lowered carrying capacity. If the water is cleared and the fluctuation remains, the fluctuation will become the primary limiting factor. The crop will rise to the extent that the fluctuations (the new primary limiting factor) permit an expansion of the standing crop. If two factors each cause the standing crops to be lowered 50 percent, their combined effect is equal to the product of the relative lowered standing crops, example - 50 x 50 = 25 percent. Using the data from figure one when the water transparency decreased from 4.1 to 2.6 feet, the standing crop decreased 25 percent, and in the impoundment, the standing crop was 6 percent of maximum at a transparency 2.6 feet. The product of these (0.06 times 0.25) is 1.5 percent, so the standing crop is 1.5 percent of potential maximum. Where its water is not impounded, clearing it should increase the standing crop substantially.

All of the problems encountered can be reduced into five categories, and in any situation they may or may not operate independently. For example, high water velocities can erode stream bed and banks and cause high turbidities, but high turbidities, (low transparency) can also be caused by turbid discharges from the adjacent land or plankton from lakes. The five categories are (1) Excessive force of water, (2) Stability and quality of bottom soils, (3) Extent and variation in water depths, (4) Amount of light present, and (5) Amount of cover for organisms.

Since any of the physical stress conditions can hold aquatic populations at lower than optimum levels, the problem becomes how to detect and correct them. Some problems can only be corrected by altering the physical characteristics of the environment, such as stream bank and bed erosion, stream gradient, widths, depth, changes in water stage and substrate. Other than sound on-land erosion practices, the only way stream turbidities can be controlled is to provide stable banks, and beds by improvement practices such as cover planting and rip-rapping. Many rivers and streams have water velocities that are too high for the substrate present, and the only way to stabilize the soils is to reduce the stream gradient or prevent erosion with coarse substrate. There are two ways stream gradients can be decreased: (1) lengthen with stream meanders, (2) or with check dams of boulders and rubble (under natural conditions rapids and riffles).

Depths can be increased by narrowing the waterway and/or increasing its length, and can be decreased by making a stream shallower and wider (channeling). Fish habitat is ordinarily increased by providing an alternation of shallow fast flowing water with coarse substrate to provide food (invertebrate drift) and deeper holding water with cover.

The usual way of correcting problems in trout streams is to adjust the depth, width, and stream velocity by narrowing the stream width and creating deep holes with non-erodable materials, by alternating the direction with deflectors and by creating plunge pools or scour holes under logs, so that space and habitat is provided for all types of aquatic animals. Conversely, problems are usually created and populations of animals decline when waterways are widened to accommodate excess flows of water, because holding water and food producing areas (riffles and rapids), are usually destroyed.

Problems related to water volumes fall into three categories (1) excessive flows in the spring and after summer storms, (2) receding levels during the summer productive period, and (3) low winter flows. In natural streams, changes in water stage can be reduced to some extent by reducing runoff from the land or by water storage reservoirs. Where reservoirs are present, changes in stage can be modified considerably by storing water during peak runoff periods and releasing it when flows are lower. Generally, reservoirs are designed with operating limitations, the chief one being the storage capacity. Frequently, desired flows cannot be provided throughout the year, so discharges should be regulated to provide a reasonable minimum discharge that does not fluctuate excessively, especially during the summer, and that provides sufficient water for successful fish spawning in the spring. To provide optimum conditions at low flow riffles should have an average depth of one foot, pools should have an average depth at least three feet, and surface water velocities in riffles with hard (gravel or rubble) bottoms should range from 1.5 to 2.2 feet per second. Note that when depth and velocity become fixed parameters, only stream width, and slope and bottom roughness can be used to adjust the streams physical characteristics to attain favorable environmental conditions. Since single purpose high flow channels are ordinarily incompatible with good quality aquatic populations so channels should be designed for two flow stages, a high flow and a low flow.

Following is a key to aid in diagnosing stream quality and is based on readily observed conditions.

A KEY TO STREAM QUALITY AS INDICATED BY STREAMSIDE CONDITIONS

I. Bottom sand, silt, or clay

A. Silt present along stream margin. (Water velocities not perceptible at low flow).

1. Plants absent - Scouring with a large volume of water is indicated. Production of fish and benthos is low. Frequently low water transparency also limits plant and animal abundance.
2. Plants present- Problems usually restricted to lack of cover for fish which are concentrated in pools and holes under fallen trees, or lakes or pond like areas. Plant communities frequently dense along the stream's margin. Production of fish and benthos is usually good.

B. Silt absent along the stream margin. (Water velocities ordinarily under 1.7 feet per second at low flow).

1. Aquatic plants absent:

a. Banks raw or with large cracks parallel to edge - Stream gradients are over 0.7 feet per mile. Sandy and clay banks erode when water velocities are too high. Clay banks resist erosive forces better than sand so clay soils can produce more invertebrates than sandy soils, but both are relatively unproductive. Trees on the streams edge lean towards the stream and eventually fall in. Low water transparency is likely to limit plant and animal abundance.
b. Banks grassed or with brush - Stream gradients under 0.7 feet per mile. Banks have vegetation but stream velocities are high enough to erode sand and clay bottoms at high flow. Sometimes filamentous algae is present late in the summer. Production is low, but can be fairly high in isolated areas.

2. Aquatic plants present:

a. Aquatic plants present along margin or throughout the stream.
This is usually a newly established community at low flow or stabilized flow and probably transitory. Under more extreme conditions it would be 1.a. or 1.b. Production is temporarily higher.
b. Aquatic plants occasionally present.
Rooted aquatic plants, especially emergents, occur in specialized locations such as banks with water seepage, or backwater pools, otherwise the waterway is similar to 1.a. or 1.b. Frequently water stages are variable. Production is high in isolated areas.

II. Bottom of stream gravel, rubble, and/or boulder.

A. Rocks and gravel not slippery.

No growths of periphyton diatoms are present which indicates excessive stream velocities - which has moved the substrate extensively. In southeastern Minnesota, flash scour floods can cause this absence of growth, and rocks are their natural color instead of a grayish to black color of rocks in streams. Rocks at the edge of a stream will be like this when water levels are temporarily high. It takes about a month for diatoms to establish a good growth on an artificial substrate. These areas are unproductive.

B. Rocks and gravel slippery

1. Little or no algae and moss present.

Conditions similar to II.A. except that a community of diatoms has had time to develop - A condition that is present in gravel riffles where water velocities are high. These areas are moderately productive.

2. Rooted aquatic plants and periphyton distinctly present -

a. No rooted aquatic plants present, but algae and moss are present - usually this is the condition that prevails in riffles or rapids with high water velocities (over 2.2 feet per second).

(1) Periphyton, algae, and moss present in center of stream only. This indicates variable water stages or a stream at a high stage. Productive in center only.

(2) Periphyton, algae, and moss present across the entire stream. If dead algae and moss is present on exposed rocks, the stream has reached a very low stage, sometimes unusually low. Most very productive riffles and rapids with very high water velocities fall in this category.

b. Rooted aquatic plants present - Water velocities, water stages, and substrate suitable for producing aquatic plants along margin and/or across the stream.

(1) Plants only along margin -
Water velocities are high enough to limit plant growth in the center and/or water not clear enough to allow plant growth in center of stream. Rooted aquatics on dry land indicates very low water levels and/or variable yearly runoff in the watershed. Most productive along margin.

(2) Plants present throughout the stream -
Ordinarily this condition is found in shallow pools and riffles with relatively low water velocities. Small sized fish are relatively abundant. These are productive areas.

REFERENCES

Bayless, J. and W. B. Smith
1967. The effects of channelization upon the fish populations of lotic waters in Eastern North Carolina, N. Car. Wildlife Res. Comm., Div. of Inland Fisheries, 14 pages.

Carlander, K. D.
1955. Standing Crop of fish in lakes. J. Fish Res. Bd. Canada - Vol. 12(4) 1955 - p. 543-570.

Clay, C. H.
1961. Design of fishways and other fish facilities. Dept. of Fisheries of Canada - pp. 188-192.

Congdon, J. C.
1971. Fish populations of channelized and unchannelized sections of the Chariton River, Missouri. North Central Div., Am. Fish Society - Special Publication 2 - pp. 52-62.

Emerson, J. W.
1971. Channelization: A case study - Science Vol. 173 pp. 325-326.

Hansen, D. R.
1971. Stream channelization effects of fishes and bottom fauna in the Little Sioux River, Iowa. North Central Div. Am. Fish Cociety - Special Publication 2 - pp. 29-51.

Hayne, D. W. and R. C. Ball
1956. Benthic productivity as influenced by fish predation Limnol. and Oceanogr. Vol. 1 - pp. 162-175.

Himer, L. E.
1947. Effects of a severe flash flood on fish and fish foods in Crooked Creek, Houston Co., Minn. Minn. Dept. Cons., Div. of Game and Fish. Inv. Report 72.

Hunt, R. L.
1965. Surface-dirt insects as a trout food in the Brule River. Wisc. Ac. Sciences, Arts, and letters. Vol. 54 - pp. 51-61.

Hunt, R. L.
1971. Responses of a brook trout population to habitat development in Lawrence Creek. Wisc. Dept. of Nat. Res. Tech. Bul. 48. 35 pp.

Hyues, H. B. N.
1972. The ecology of running waters - Univ. of Toronto Press. 555 pp.

REFERENCES (Cont'd.)

Johnson, R. E., J. B. Moyle, W. A. Kenyon
1949. A biological survey and fishery Management plan for the streams of the Root River Basin, Minn. Dept. Cons., Div. of Game & Fish. Inv. Report 87. 129 pp.

King, H. W.
1929. H dbook of Hydraulics. McGraw Hill Book Co., Inc. p. 252-282, 433-437.

Kueben, J. H., W. Niemuth, and A. R. Peterson
1959. A biological reconnaissance of the upper St. Croix River. Minn. Dept. Cons., Div. Game and Fish. Inv. Report 239, 46 pp.

Langbein, W. B. and L. B. Leopold
1966. River Meanders - Theory of Minimum variance. USDI Geological Survey Proj. paper 422 - H. 15 pp.

Leopold, L. B. and J. P. Miller
1956. Ephemeral streams Hydraulic factors and their relation to the drainage net. USDI Geological Survey Prof. paper 282A. 27 pp.

Leopold, Luna B. and T. Maddock
1953. The hydraulic geometry of stream channels and some physiographic implications, USDI Geological Survey Prof. paper 252 - 57 pp.

Morris, L. A., R. M. Langmier, T. R. Russel
1968. Effects of main stem impoundments and channelization upon the limnology of the Missouri River. Neb. Trans. Am. Fish Soc. Vol. 97 No. 4 pp. 380-397.

Moyle, J. B.
1940. A biological survey of the Upper Miss. River system Minn. Dept. Cons. Div. Game and Fish. Inv. Report 10, 68 pp.

Moyle, J. B. and W. A. Kenyon
1947. A biological survey and fishery management plan for the streams of the St. Louis River System. Minn. Dept. Cons., Div. of Game and Fish Inv. Report 69, 161 pp.

Moyle J. B.
1952. Some aspects of the chemistry of Minnesota Surface waters as related to fish and game management, Minn. Dept. Nat. Res., Div. of Fish & Wildlife, Inv. Report 128.

Peterson, A. R.
1962. A biological reconnaissance of the Upper Miss. River. Minn. Dept. Cons., Div. of Game and Fish, Inv. Report 255. 50 pp.

REFERENCES (Cont'd)

Peterson, A. R.
1975. Analysis of the composition of fish populations in Minnesota's Rivers and streams, Minn. Dept. Nat. Res. Div. of Fish and Wildlife, Inv. Report 335, 34 pp.

Peters, J. C. and W. Alvord
1964. Man-made channel alterations in thirteen Montana streams and rivers. Trans. Am. 29th N. Am. Wildlife Conf. pp. 93-102.

Smith, L. L. and J. B. Moyle
1944. A biological survey and fishery management plan for the streams of the Lake Superior North Shore Watershed, Minn. Dept. Cons., Div. of Game and Fish Tech. Bul. 1.

Tarzwell, C. M.
1937. Factors influencing fish food and fish production in southwestern streams. Trans. Am. Fish Soc. Vol. pp. 246-254.

Ward, H. B. and G. C. Whipple
1918. Fresh-water biology John Wiley and Sons, Inc.

Waters, T. F.
1969. The turnover ratio in production ecology of fresh-water invertebrates. Am. Naturalist Vol. 103 No. 930 pp. 173-185.

Welch, P. S.
1935. Limnology, McGraw - Hill Book Co. pp. 365-394.

White, R. J. and O. M. Brynildson
1967. Guidelines for Management of trout stream habitat in Wisconsin. Dept. Nat. Res., Div. of Cons. Tech. Bul. 39, 65 pp.

Wickliff, E. L., R. S. Roach
1966. Some studies of impounded waters in Ohio., Trans. Am. Fish Soc. Vol. pp. 76-86.

STANDING CROPS OF INVERTEBRATES (BENTHOS) IN THE MISSISSIPPI RIVER AND SOME TRIBUTARIES AS AFFECTED BY WATER TRANSPARENCY IN IMPOUNDED AND NONIMPOUNDED WATERS (DEPTH - 1 TO 4 FT.)

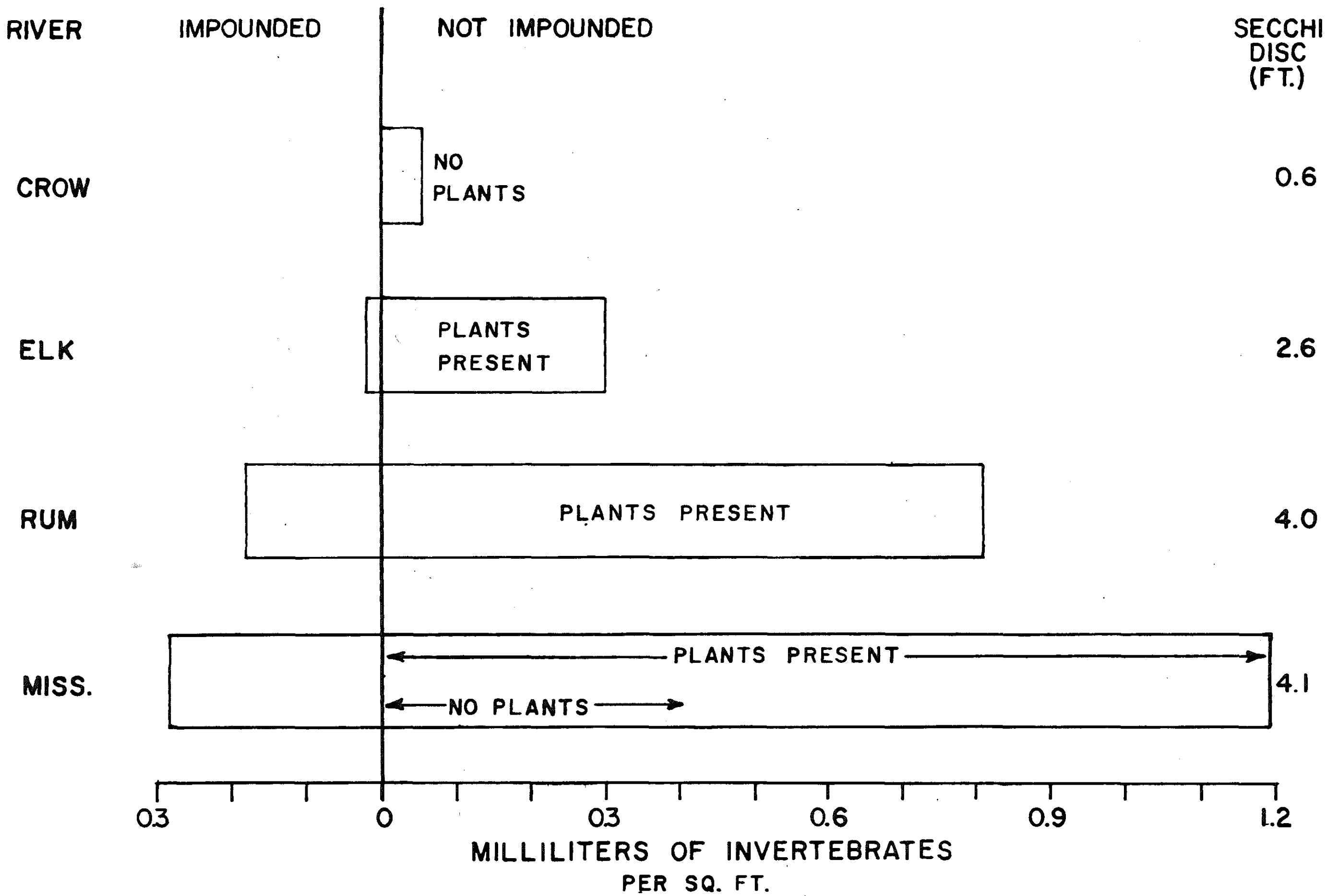


FIGURE 1

STANDING CROP OF BENTHOS IN HEADWATERS RESERVOIRS IN VARIOUS ZONES (WATER LEVEL FLUCTUATION AND EROSION, LITTORAL, AND PROFUNDAL)

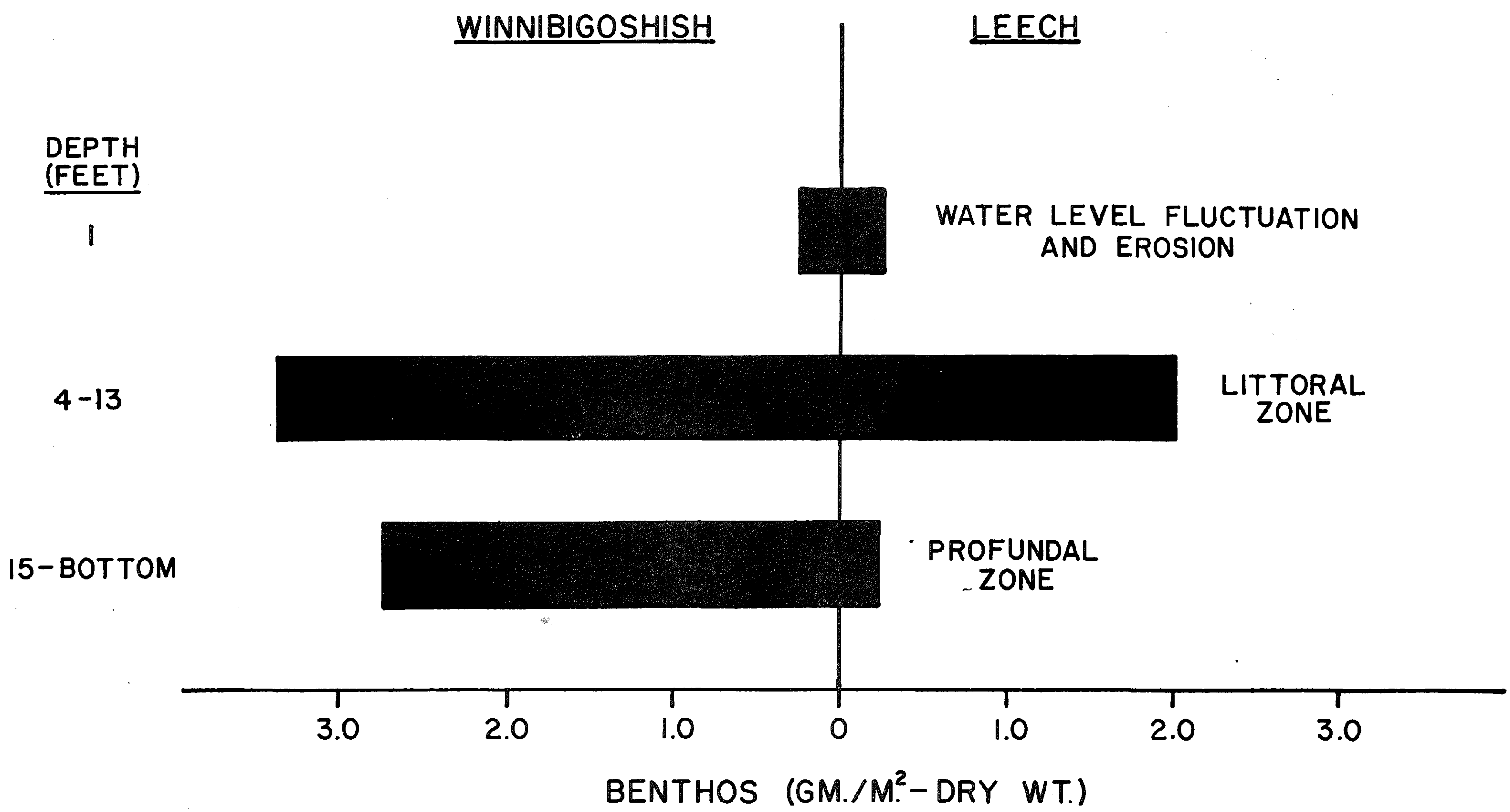


FIGURE 2

CHANGES IN THE STANDING CROP OF BENTHOS FROM THE RIVER ABOVE TO THE RIVER BELOW THE IMPOUNDMENT ON RUBBLE BOTTOMS

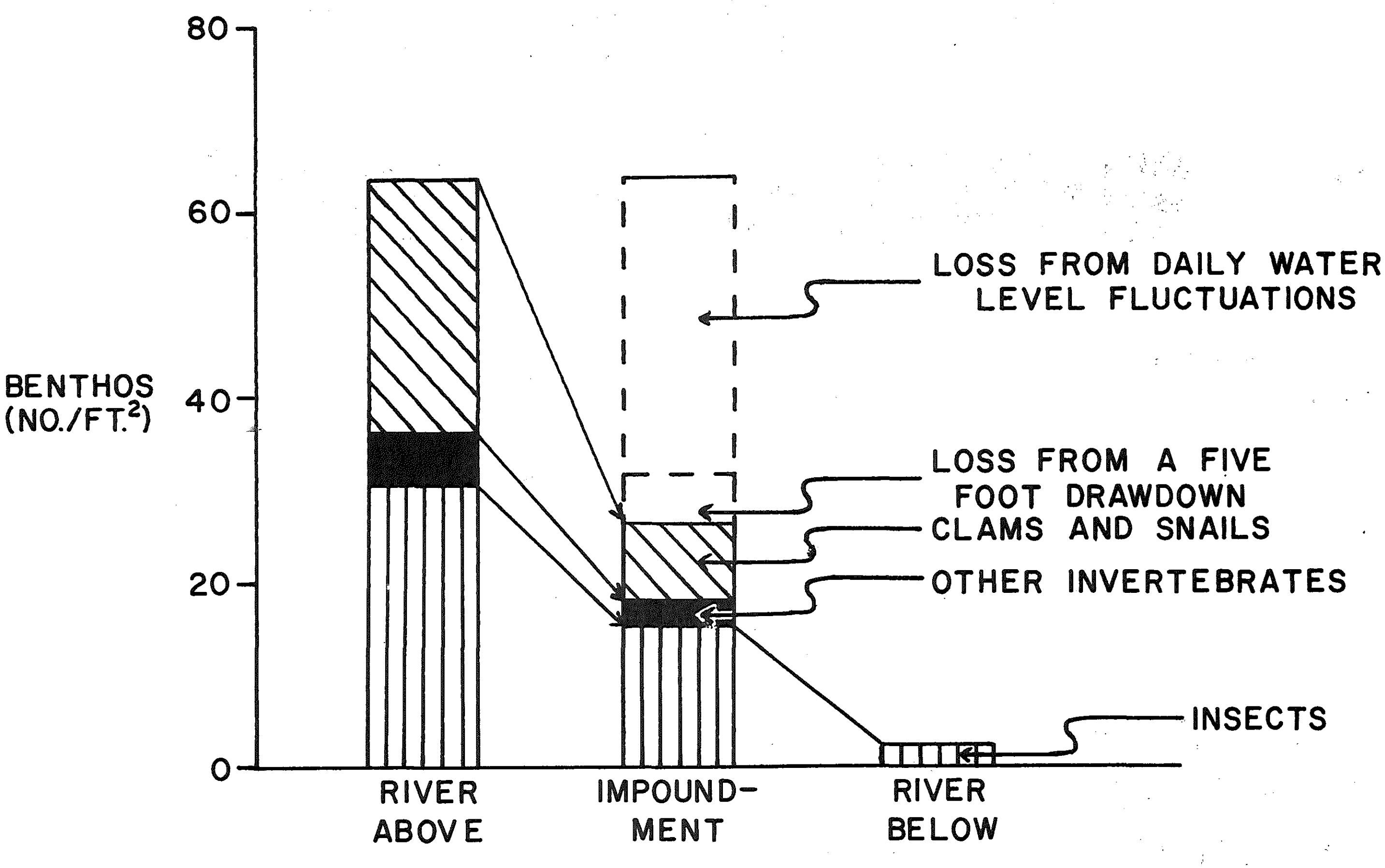


FIGURE 3

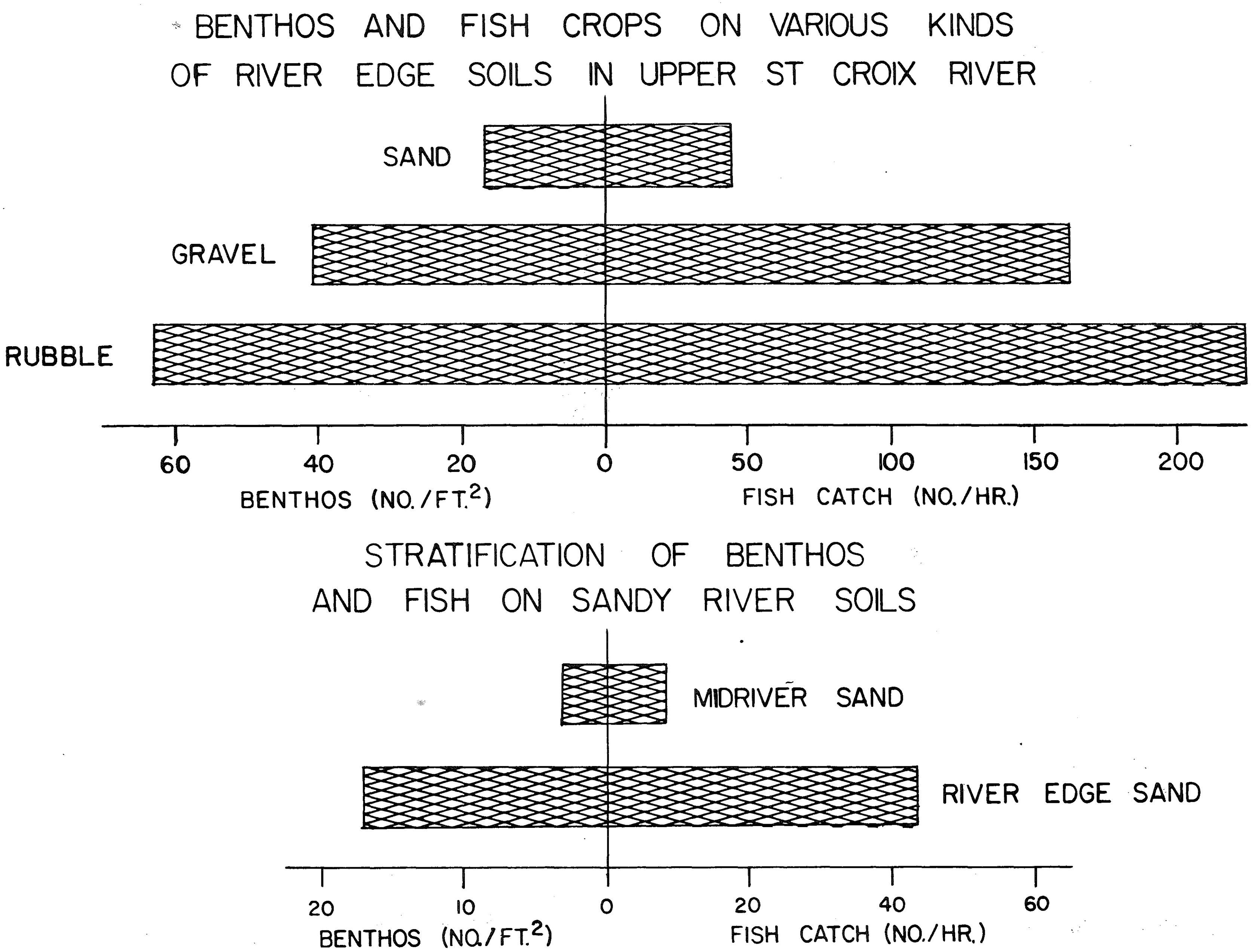

BENTHOS AND FISH CROPS ON VARIOUS KINDS OF RIVER EDGE SOILS IN UPPER ST CROIX RIVER
SAND
GRAVEL
RUBBLE
60
40
20
0
50
100
150
200
BENTHOS (NO./FT.2)
FISH CATCH (NO./HR.)
STRATIFICATION OF BENTHOS AND FISH ON SANDY RIVER SOILS
MIDRIVER SAND
RIVER EDGE SAND
20
10
0
20
40
60
BENTHOS (NO./FT.2)
FISH CATCH (NO./HR.)

FIGURE 4

STANDING CROPS OF FISH AND BENTHOS AND THE EFFECTS OF PHYSICAL STRESS (CHANGES IN WATER LEVELS AND FLOWS) ON RUBBLE BOTTOMS

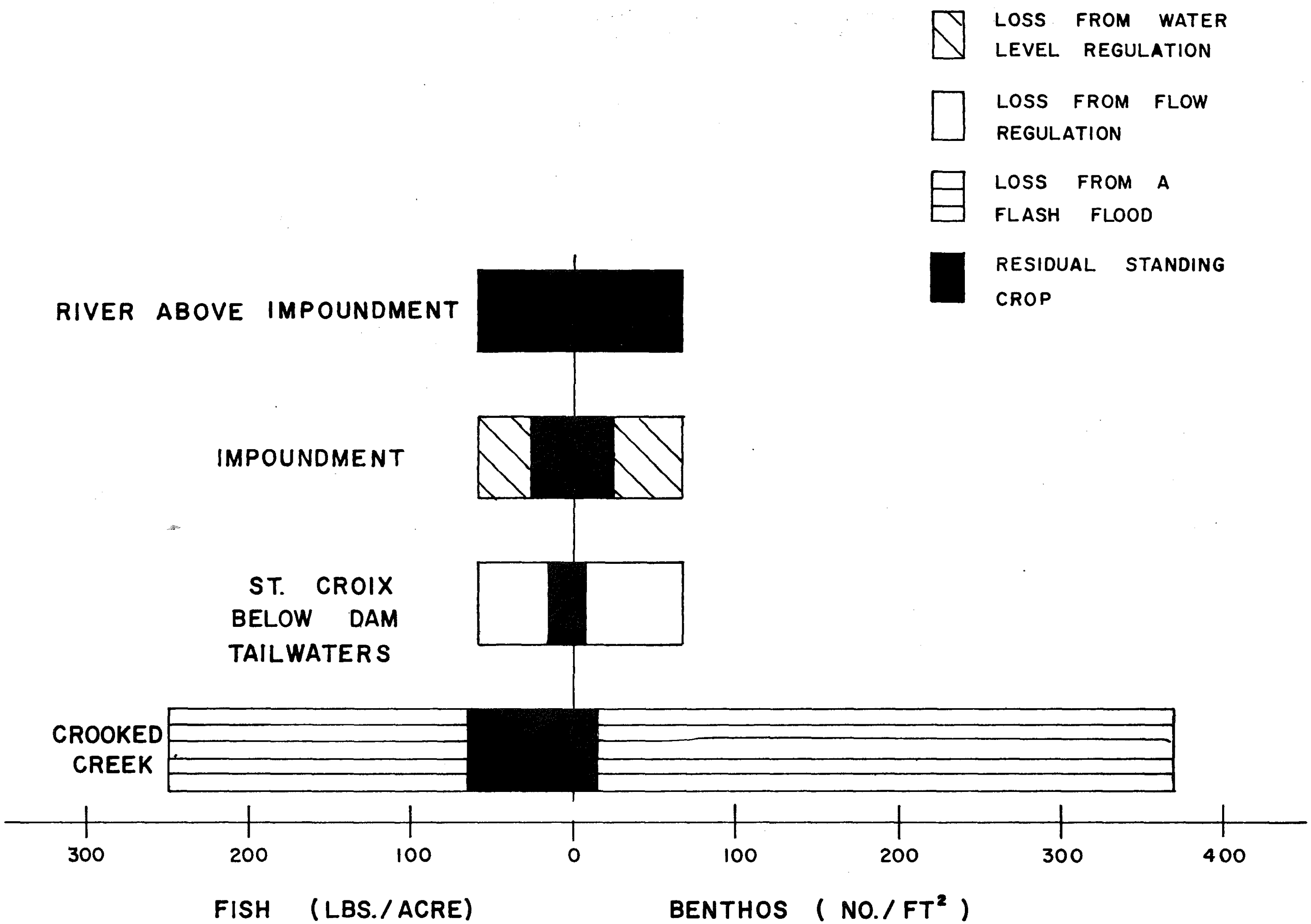


FIGURE 5

KINDS OF FOOD IN THE STOMACHS OF TROUT IN A NORMAL SITUATION AND AFTER A FLASH FLOOD

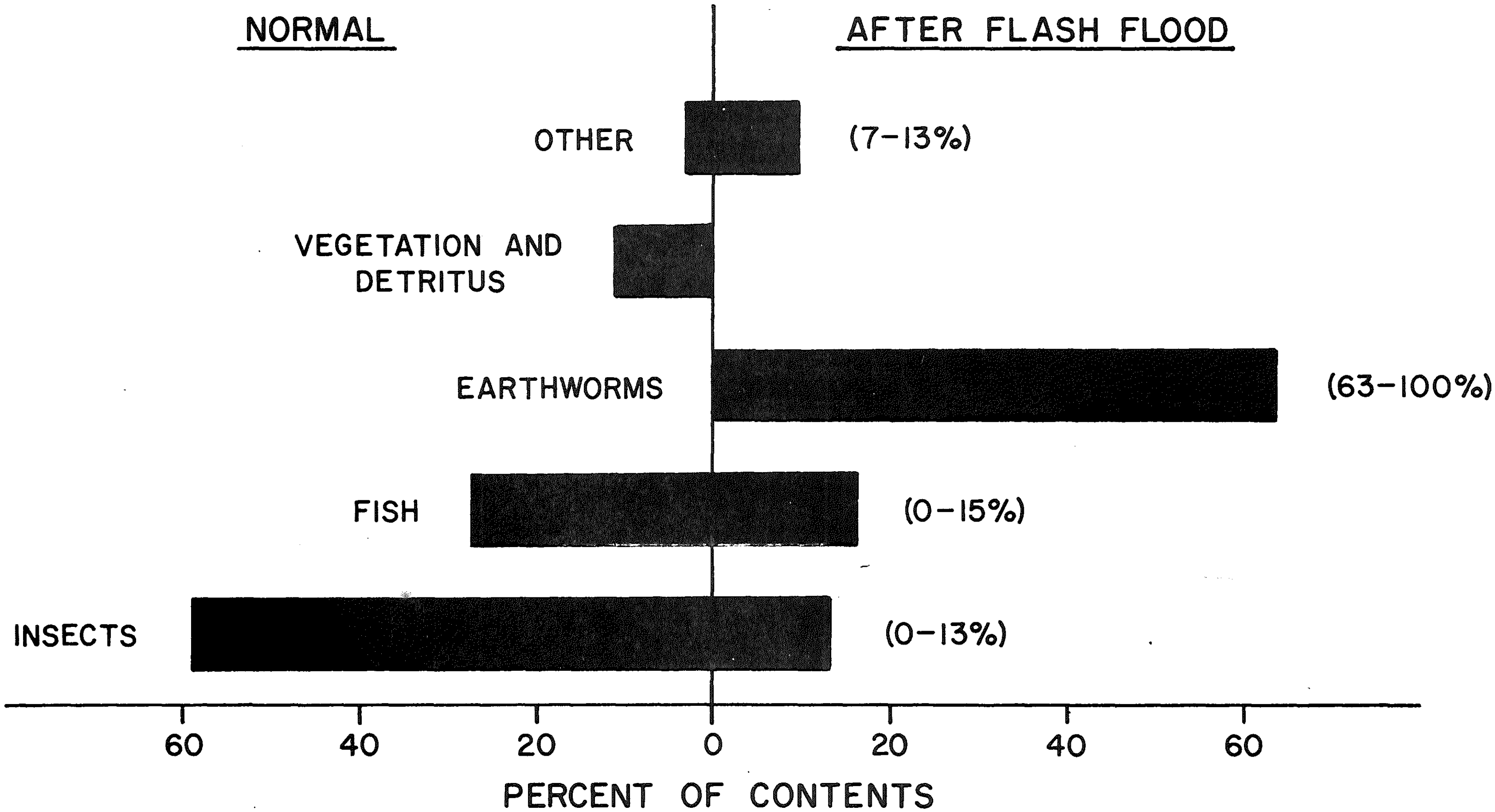
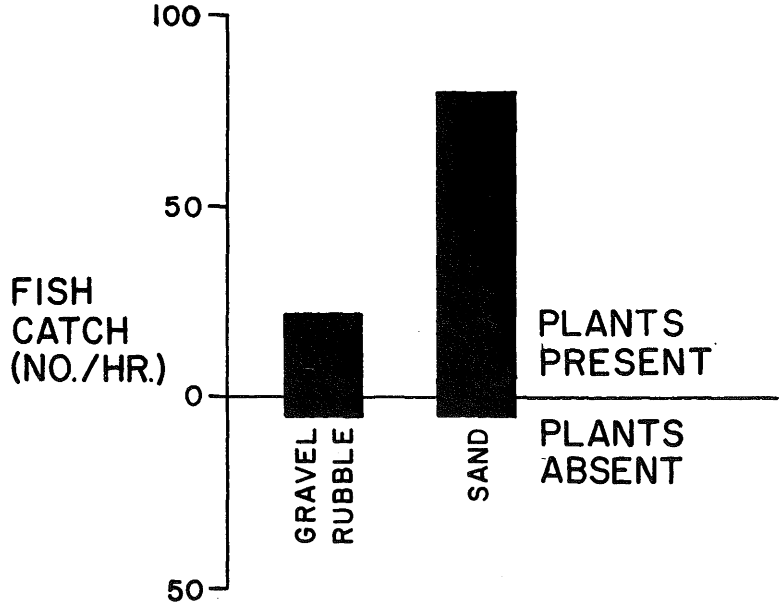


FIGURE 6

CATCH OF YOUNG-OF-YEAR FISH AND RELATIONSHIP TO AQUATIC PLANTS AND KIND OF SOIL IN THE IMPOUNDMENT



PERCENT COMPOSITION OF THE CATCH OF FISH IN AND BELOW IMPOUNDMENT

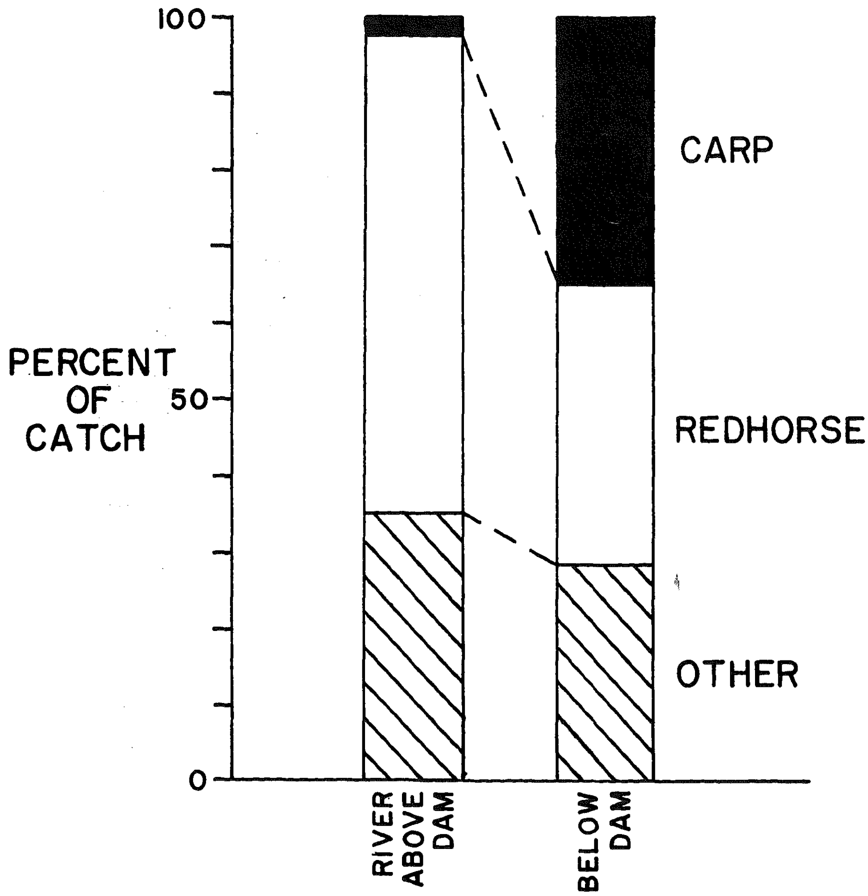


FIGURE 7

FISH CATCHES ON PRODUCTIVE BOTTOMS ABOVE AND IN IMPOUNDMENTS

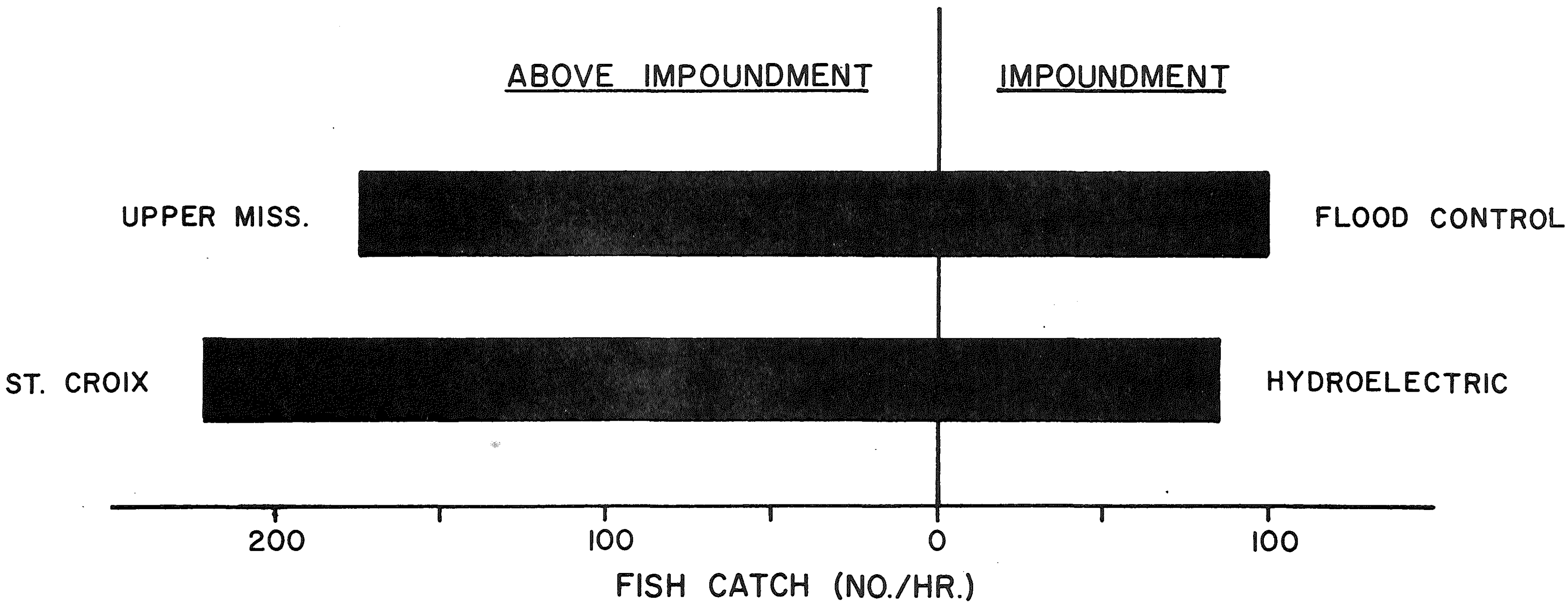


FIGURE 8

RELATIONSHIP OF BENTHOS CROP AND FISH DENSITY IN STRATIFIED RIVER SAMPLES IN GOOD QUALITY WATER

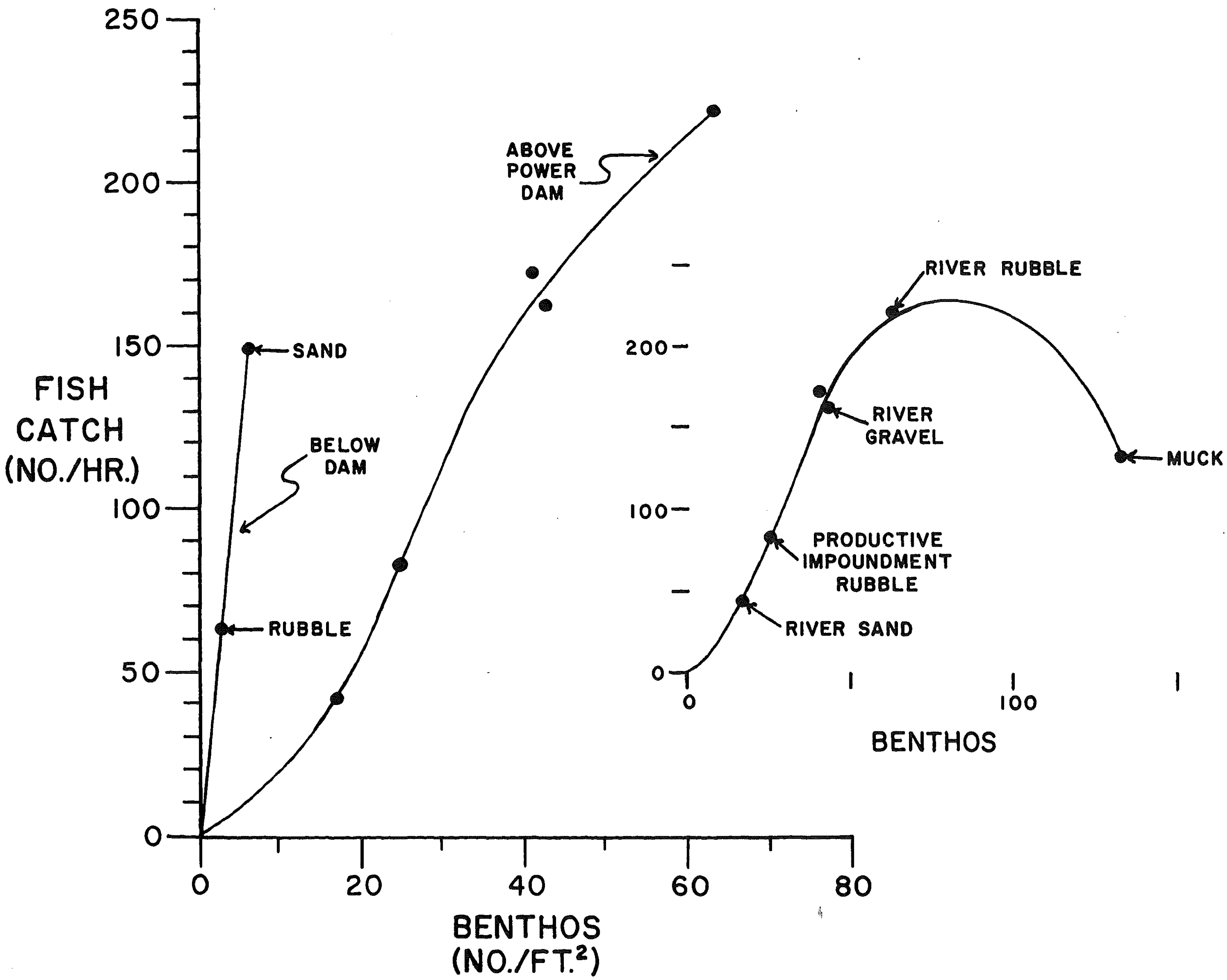


FIGURE 9

DENSITY OF INSECTS AND INSECT LARVAE (BENTHOS) IN THE UPPER MISSISSIPPI (M), ROOT (R), NORTH SHORE (N), AND ST. LOUIS (S) RIVER SYSTEMS

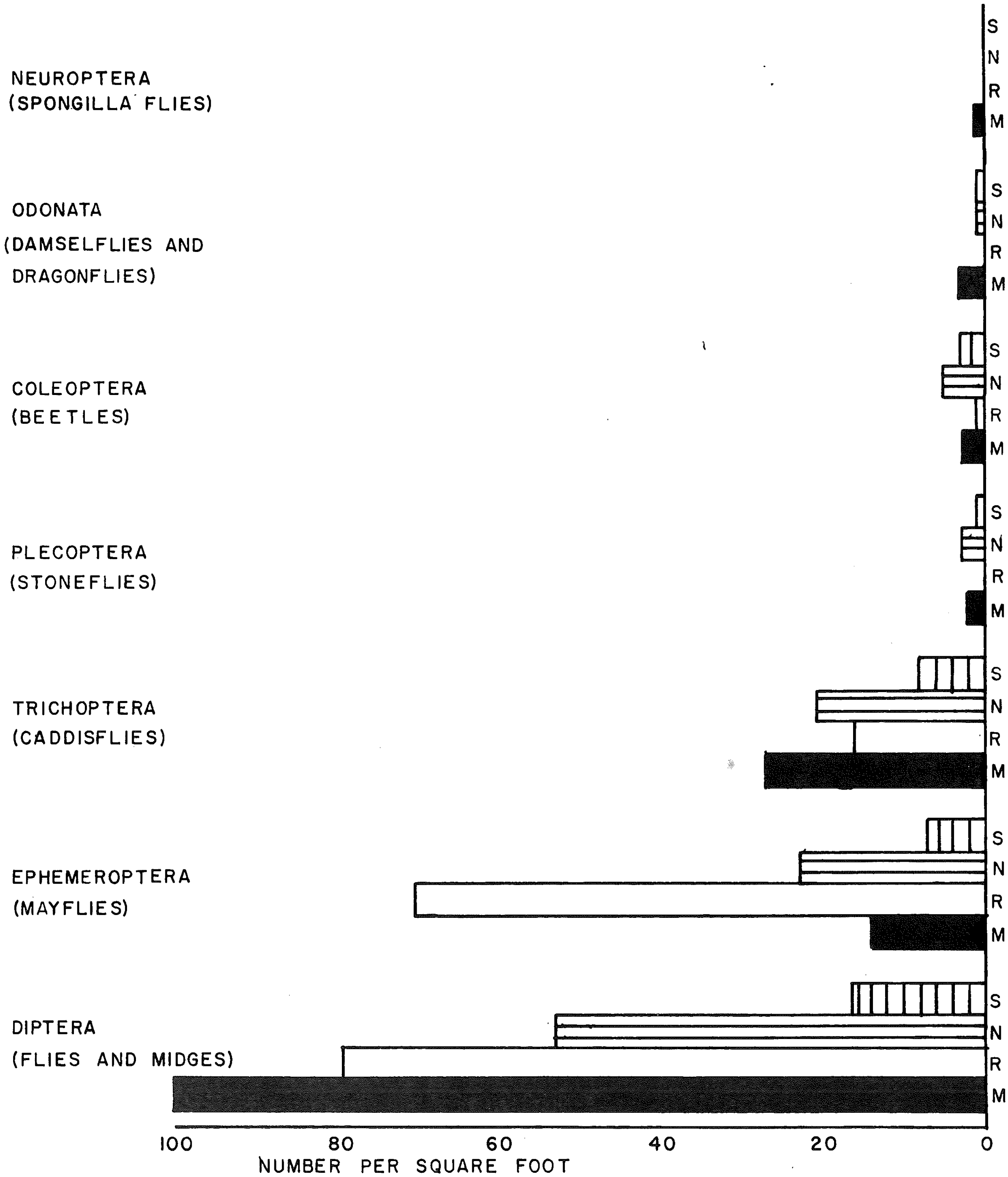


FIGURE 10

DENSITY OF BENTHOS (EXCLUDING INSECTS) IN THE UPPER MISSISSIPPI (M), ROOT (R), NORTH SHORE (N), AND ST. LOUIS (S), RIVER SYSTEMS.

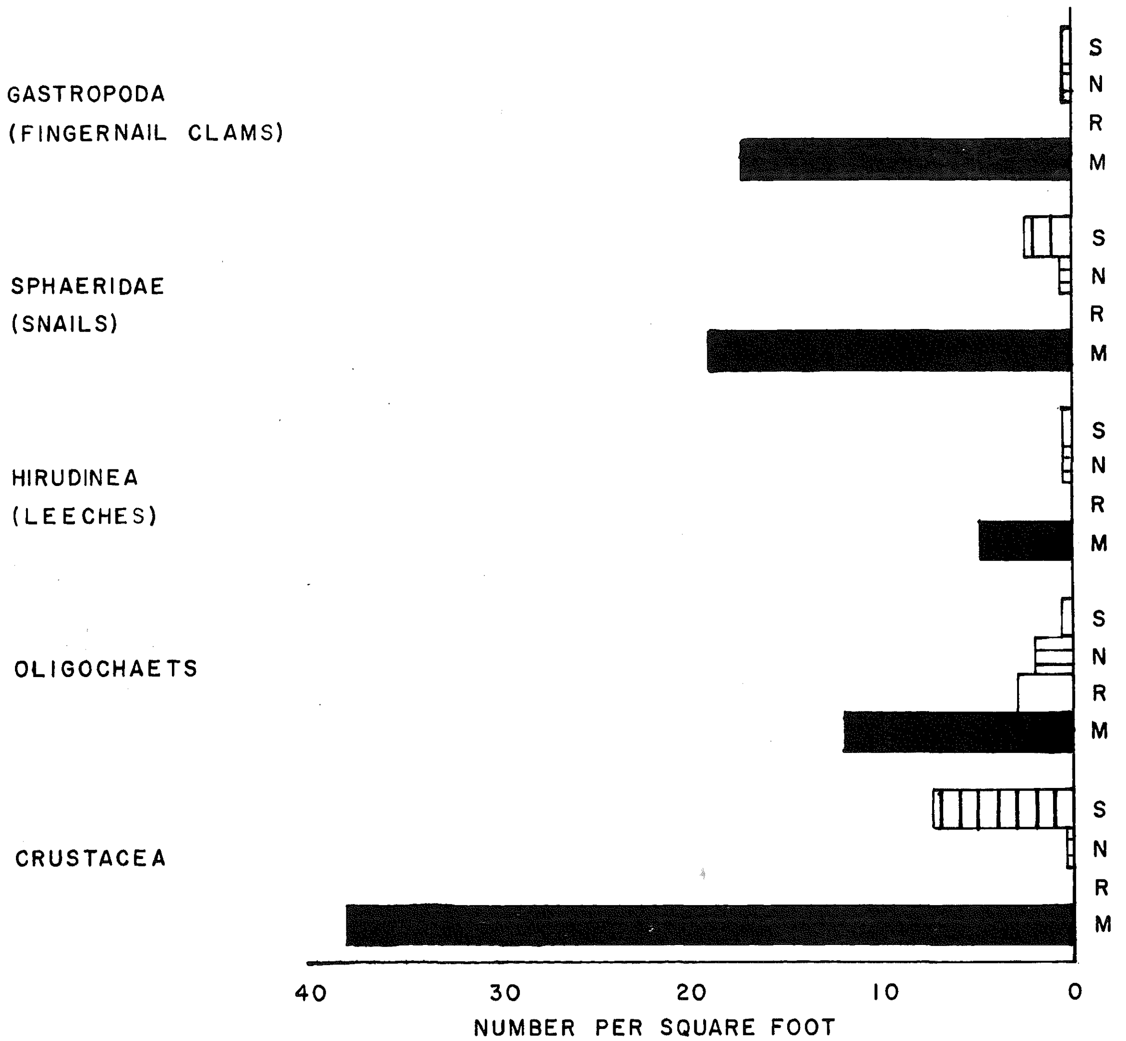


FIGURE 11

NUMBER OF MIDGES AND OTHER AQUATIC INSECTS IN THE ST. CROIX RIVER ON VARIOUS KINDS OF SUBSTRATE

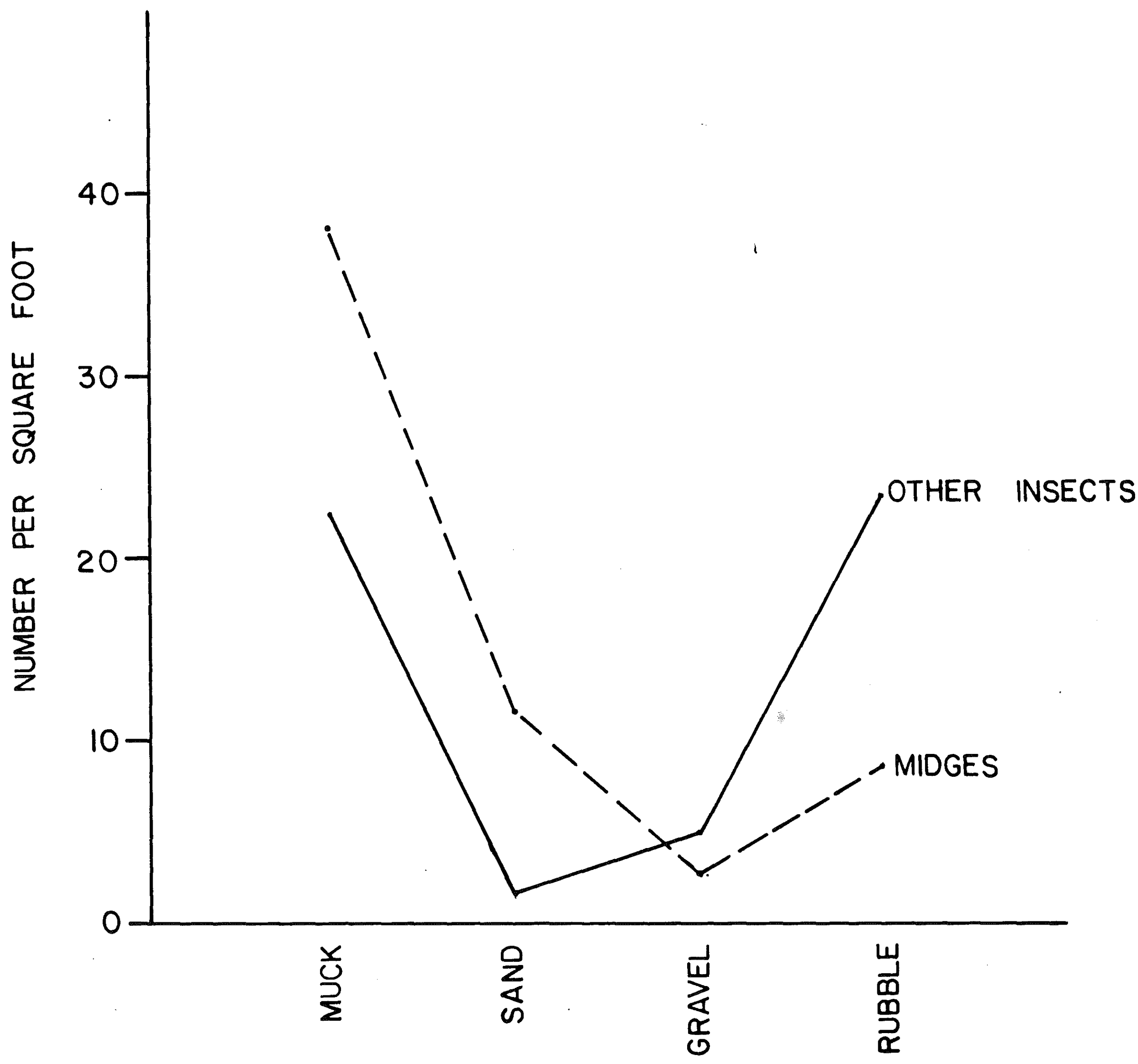


FIGURE 12

CALCULATED RELATIONSHIP OF AVERAGE WATER VELOCITY TO STREAM GRADIENT IN NORMAL STREAMS AT ORDINARY LOW FLOW WHERE n = COEFICIENT OF ROUGHNESS AND HYDRAULIC RADIUS (r) APPROXIMATES AVERAGE DEPTH.

$v = (1.486/n)(r^{0.67})(s^{0.5})$

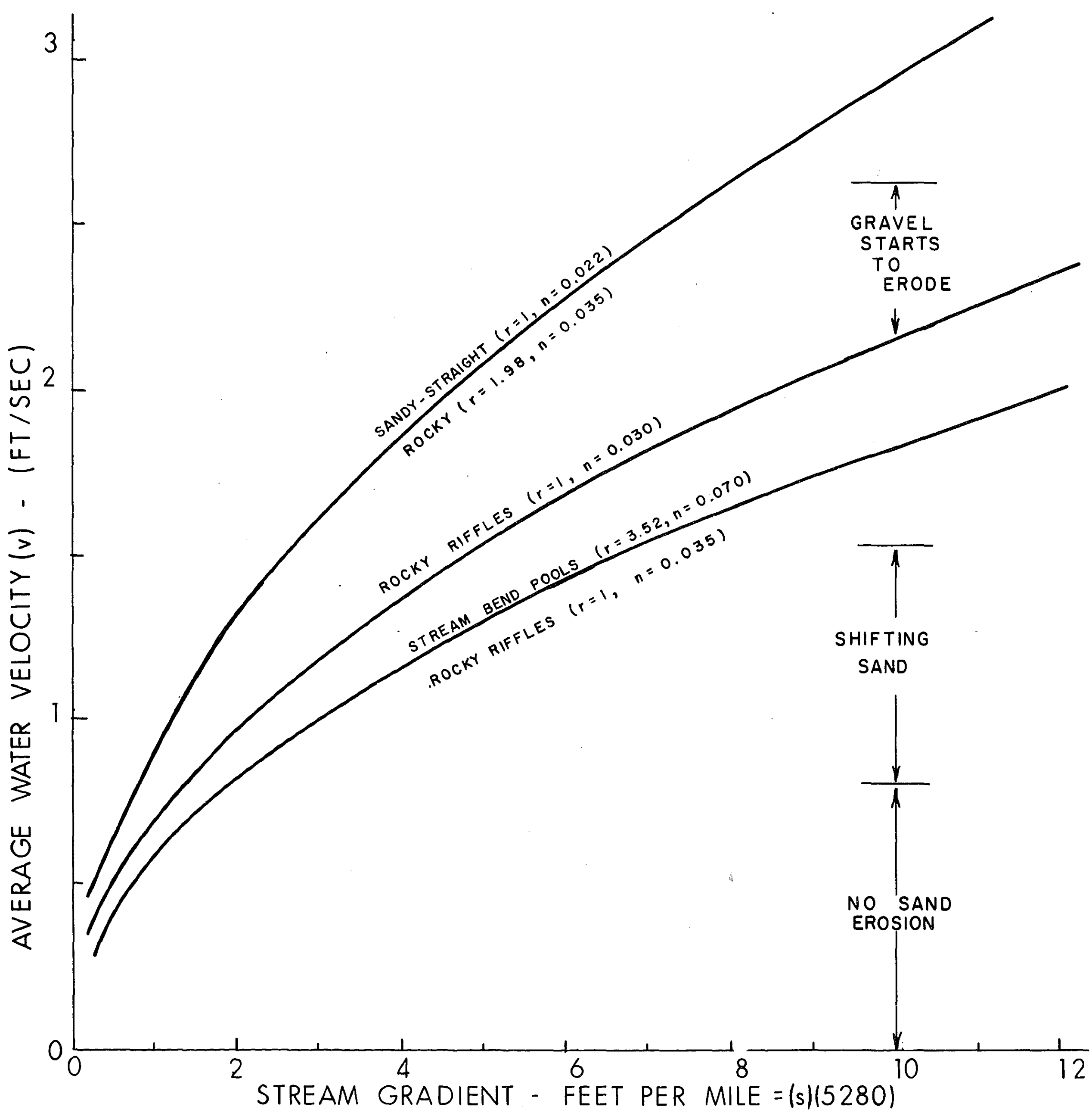


FIGURE 13

STANDING CROP OF BENTHOS IN POOLS & RIFFLES, AND ON BEDROCK AND THEIR RELATIONSHIP TO THE WATER'S ALKALINITY (DATA FROM TARZWELL - 1937)

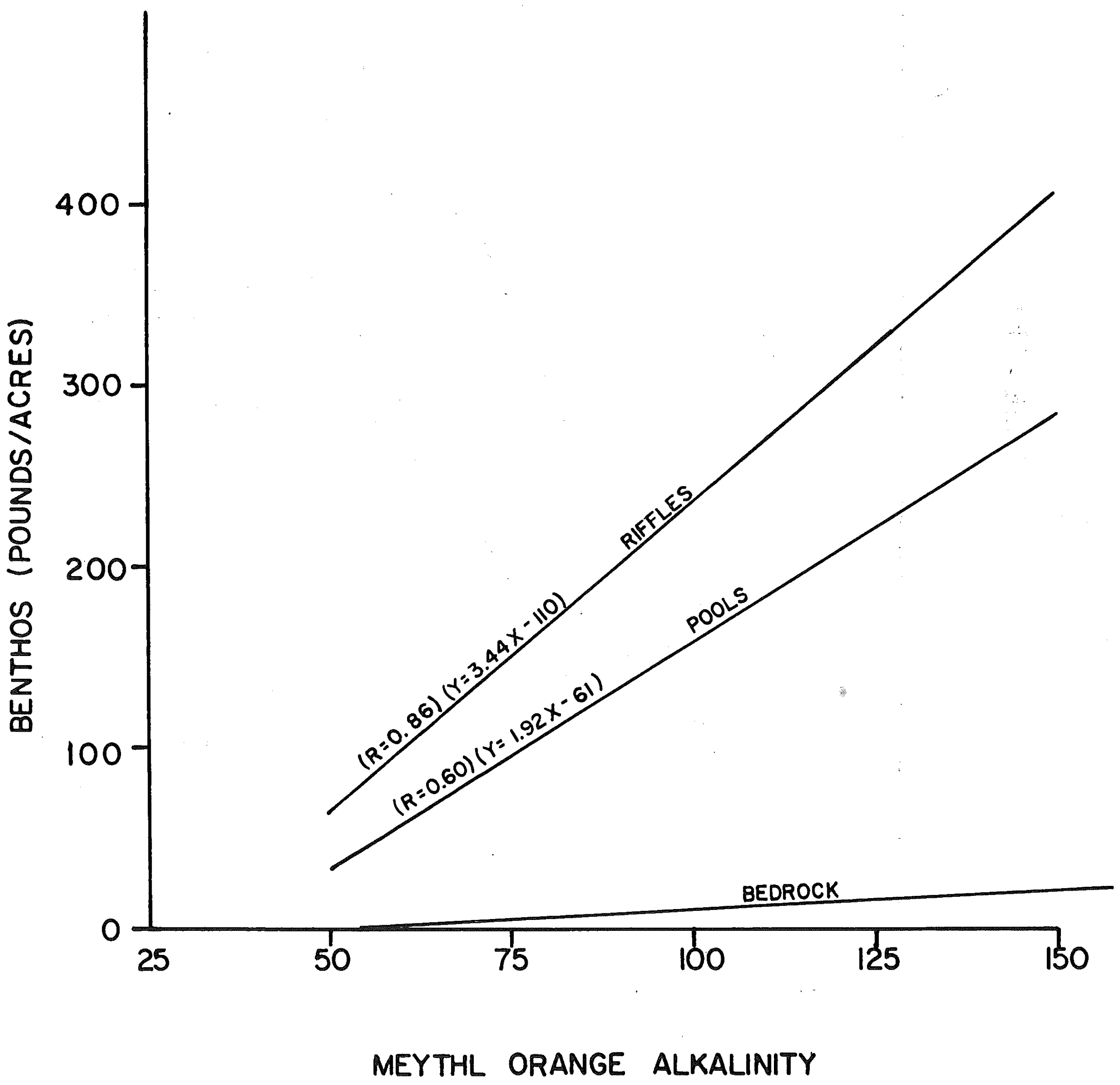


FIGURE 14

CHANGE IN WATER TEMPERATURES IN TWO SOUTHEASTERN MINNESOTA STREAMS FROM MORNING TO MID AFTERNOON ON CLEAR DAYS

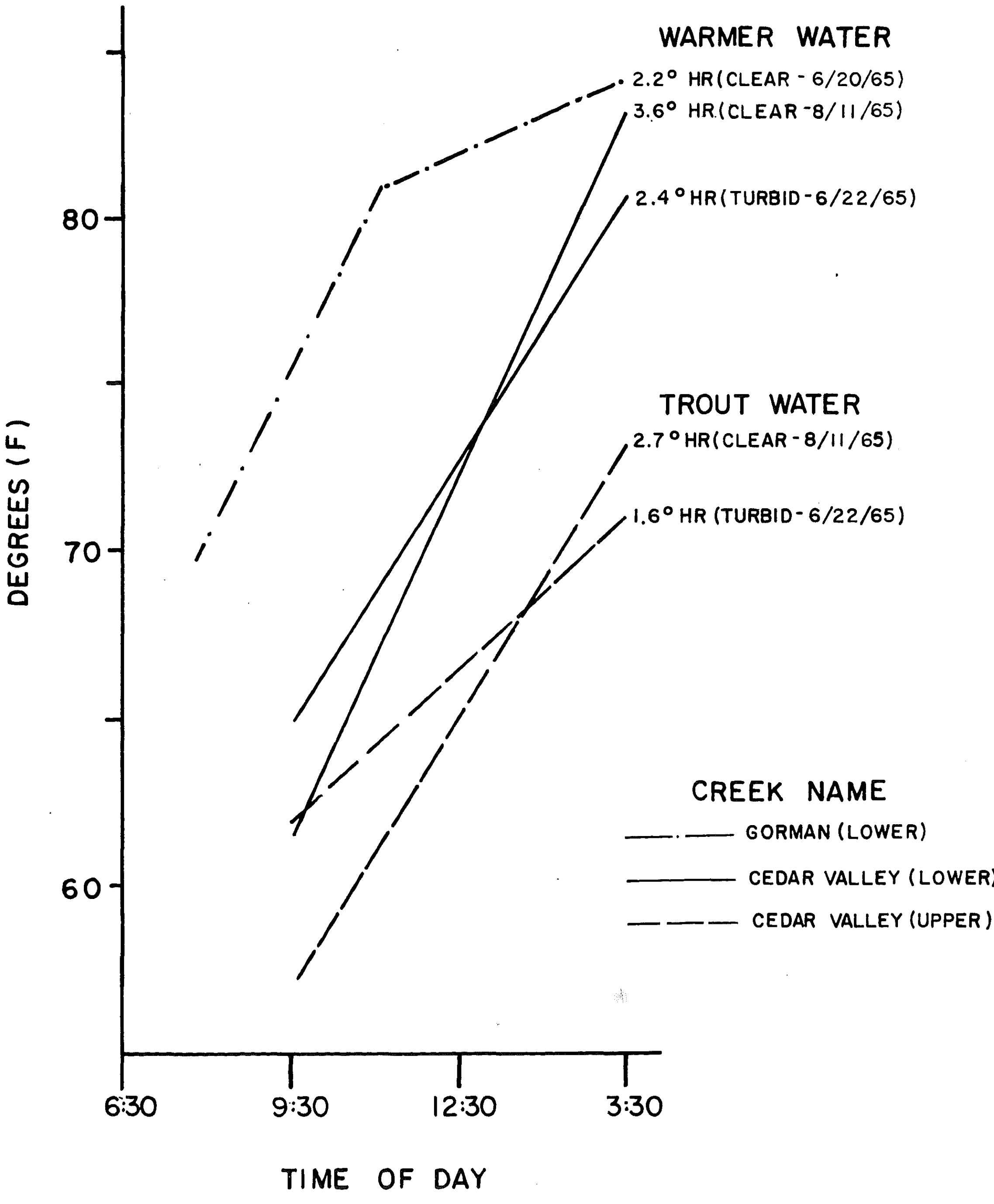


FIGURE 15