COMMUNITY STRUCTURE OF BENTHIC MACROINVERTEBRATES IN AN INTERMITTENT STREAM RECEIVING OIL FIELD BRINES

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PREFACE

The objectives of the present study of community structure in a stream receiving oil field brines were to: (1) quantitatively relate community structure of benthic macroinvertebrates to physico-chemical conditions; (2) determine seasonal environmental changes; (3) determine effect of oil field brines on stream turbidity; (4) apply methods of analysis derived from information theory to benthic macroinvertebrate community structure.

Dr. Troy C. Dorris served as major adviser. Drs. L. Herbert Bruneau, Rudolph J. Miller, William A. Drew and Calvin G. Beames served on the advisory committee and criticized the manuscript. Dr. Robert Morrison directed writing the computer program for species diversity calculations. Richard Harrel helped make field collections and Kurt Schaefer helped with identification of insects.

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CHAPTER I

INTRODUCTION

Historically, the use of aquatic organisms to investigate the biology of stream pollution has had two major approaches. The earliest approach stressed the study of indicator organisms as a means of determining degree of pollution. Kolkwitz and Marrson (1908, 1909) were pioneers in the use of aquatic organisms as indicators of ecological conditions. Richardson (1928) developed a system for associating groups of bottom organisms together to indicate levels of pollution in the Illinois River. He pointed out, however, that the presence or absence of individual species was insufficient evidence to establish the fact of pollution and stressed the need for obtaining evidence by observing the dynamics of large numbers of species. Ellis (1937) noted that the use of index species as a guide to pollution is greatly complicated because the number of individuals of a species may vary over a wide range of environmental conditions. He concluded that total assemblages of bottom organisms, when used with physical and chemical data, offered a substantial method for determining pollution and that index species are of value only when used carefully with other assemblages of organisms. Organisms found in large numbers in polluted water may also be present in reduced numbers in cleaner areas (Gaufin and Tarzwell, 1952). Regional differences in species and environment prevent agreement as to the true status of indicator organisms (Gaufin, 1958). In some cases, diversity of stream fauna may simply be due to diversity of habitat (Beck, 1954).

In recent years, the second approach has become prominent. Faunal diversity, a corollary of community structure is emphasized. The community is defined by Odum (1962) as all the populations occupying a given area. Community structure may be defined in terms of species frequency, species per unit area, spatial distribution of individuals and numerical abundance of species (Hairston, 1959).

The suitability of benthic macroinvertebrates for evaluating stream conditions has been amply demonstrated (Gaufin and Tarzwell, 1952, 1956; Beck, 1954; Gaufin, 1958; Hynes, 1958, 1963; Beak, 1964). Benthic macroinvertebrates are relatively immobile and generally have aquatic stages long enough to develop a complex faunal association. They serve as natural monitors since they are directly affected by physical conditions and chemical substances in the environment. Thus, resident faunal assemblages represent the results of extreme conditions.

Some investigators have suggested that aquatic organisms can be divided into precise groups according to pollutional tolerance (Richardson, 1928; Patrick, 1951; Gaufin and Tarzwell, 1952; Wurtz, 1955; Gaufin, 1958). Presentations of data are numerous and varied. One approach frequently used is to list or describe the faunal associations encountered. An attempt then is made to correlate physicochemical conditions with biological conditions by noting the distributional pattern of organisms that occur in the community. Patrick (1949) used a system of histograms to report the results of stream surveys that included both plants and animals. Beck (1955) described a method for allotting a score or 'biotic index' to the results of biological surveys. Wurtz (1955) used a system of histograms to group the biota into burrowing, sessile, foraging and pelagic forms that were tolerant or intolerant to pollution. Gaufin (1958) classified benthic macroinvertebrates into intolerant, facultative and tolerant forms depending on their reactions to various levels of pollution. Beak (1964) proposed a biotic index with six stages ranging from normal fauna to no fauna, depending on the degree of pollution. All these methods suffer from the fact that pollution is varied and different effluents produce different effects and different ecological conditions in streams (Hynes, 1958). As a result, efforts to classify organisms as to pollution tolerance have tended to be somewhat subjective.

A quantitative, objective and universally applicable method for interpreting community structure on the basis of distribution patterns of individuals and species would be useful. Gleason (1922) plotted species accumulated versus the logorithm of the area sampled. Other investigators have used both number of species and total number of individuals in developing an index to express community diversity (Willis, 1922; Fisher, Corbet and Williams, 1943; Williams, 1947; Preston, 1948; Margalef, 1951; Patten, 1962).

Margalef (1956b) suggested an index for community diversity borrowed from information theory. Information theory does not attempt to explain observed phenomena, but only provides the amount of information required to explain them (Hairston, 1959). Community diversity is determined by numbers of species and total numbers of individuals. When all individuals belong to separate species, diversity is maximum, but when all belong to one species it is minimum. Diversity ordinarily is intermediate in most communities. Diversity indices are useful in summarizing large amounts of data about numbers and kinds of organisms (Patten, 1962).

Diversity may be considered to be synonymous with information (Margalef, 1961). It may be calculated from numbers of individuals and species and expressed in bits, one bit being the amount of information required to specify one of two equally probable states. The amount of information contained in a natural community should exceed that in a polluted situation. Natural communities tend toward a random arrangement of organisms and more states are required to describe them. A polluted system has less randomness and is more highly organized because some species are unable to survive. The species that remain encounter less competition, thus they are able to produce large numbers of individuals if sufficient nutrients are supplied.

The concept of redundancy or repetition is important in information theory. Unequal distribution of individuals into species constitutes greater repetition, or redundancy, for the more common species. As a result, the probability that an individual belongs to a species previously recognized is increased and the amount of information per individual is reduced. Margalef (1956a) thought of redundancy as the position of a community between maximum and minimum diversity. A community of few species and many individuals should have high redundancy and low information per individual, the converse being true for a community with many species and few individuals. Patten, Mulford and Warinner (1963) defined redundancy as a measure of the extent to which dominance is expressed by one or more species.

Effective application of information theory in determining community structure requires only that organisms be recognized at the species level, though not necessarily named.

In the present study, indices derived from information theory were applied in the analysis of benthic macroinvertebrate community structure in a brine polluted stream.

CHAPTER II

DESCRIPTION OF AREA

General Description of Basin

Black Bear Creek is an intermittent stream located in north-central Oklahoma. It originates five miles east of Enid, Oklahoma, and flows eastward through Garfield, Noble and Pawnee counties to the Arkansas River eleven miles northeast of Pawnee, Oklahoma (Fig. 1). Downcutting as the result of geologic uplift in the region has formed steep banks along the creek. Deepest banks are found in lower reaches where they range from 12 to 18 m in height. The main channel is approximately 169 km long and it has an average gradient of 0.90 km (Fig. 2). Meanders are common, especially in the lower reaches. Major tributaries are located on the south side of the creek; those on the north side are short and many are unnamed. A method of drainage analysis based on the degree of branching ranks Black Bear Creek as a seventh order stream (Horton, 1945; Strahler, 1956).

Black Bear Creek drainage basin is located in the moist subhumid climatic zone (Soil Conservation Service, 1959). It has an average frost-free period of 210 days from April 1 to October 28 with a mean annual temperature of 16.2 C. Rainfall averages 80 cm in the western part of the basin and 90 cm in the eastern part but wide fluctuations occur (Fitzpatrick, Boatright and Rose, 1939; Galloway, Templin and

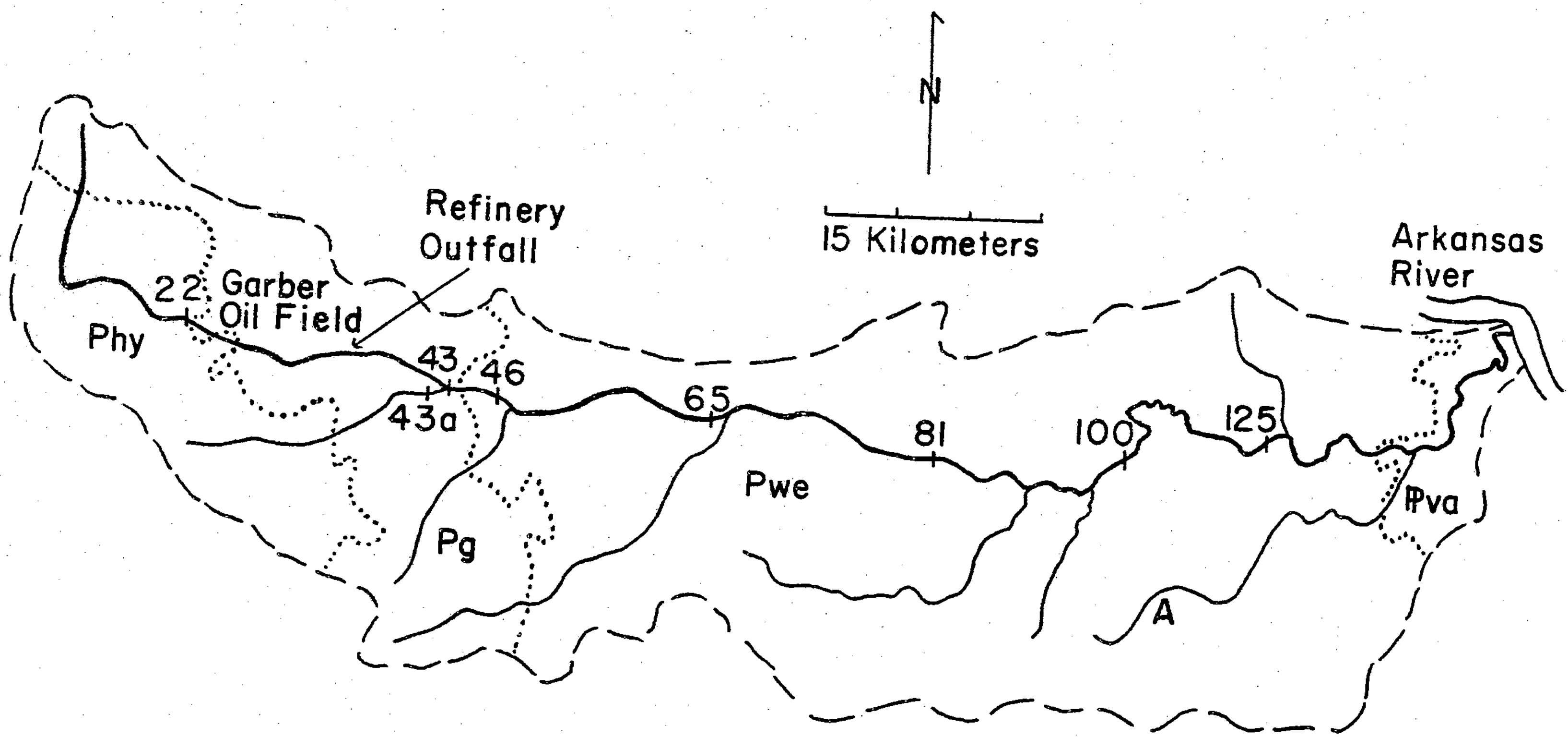

Fig. 1. Map of Black Bear Creek. Station locations indicated by numerals. Camp Creek = (A). Basin boundary = (⌒‿⌒). Formation boundaries = (. . . . .). Permian: Phy = Hennessey, Pg = Garber, Pwe = Wellington. Pennsylvanian: IPva = Vanoss and Ada.

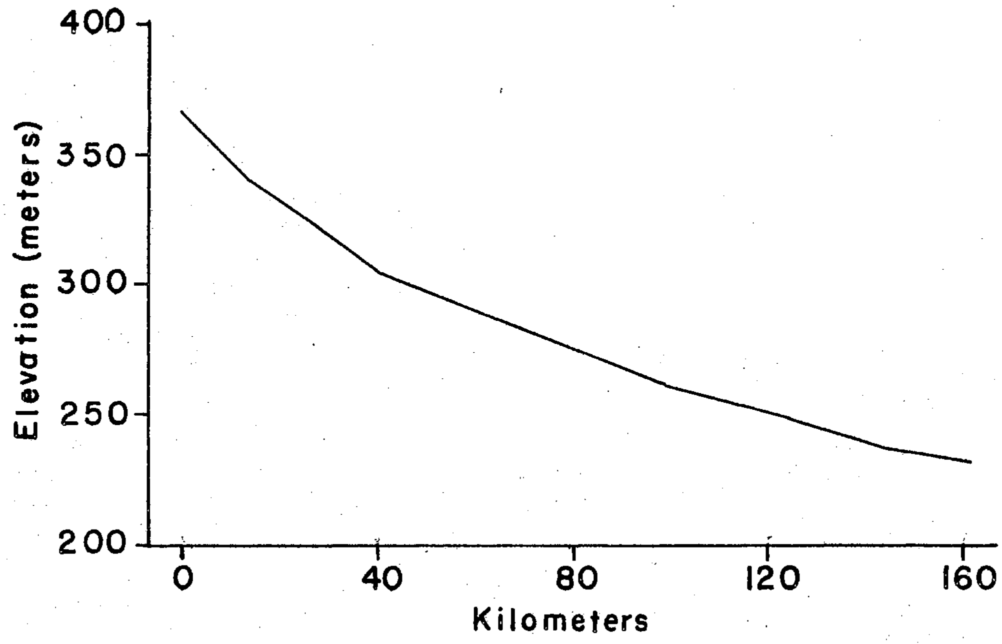

Fig. 2. Longitudinal stream profile.

Oakes, 1959). Generally, rainfall is greatest in the months of April, May and June while driest months are December, January and February (Soil Conservation Service, 1959). Wind velocities are moderately high and are greatest in March and April (Galloway et al., 1959). Average relative humidity at 2:00 p.m. is 60 percent in January, 40 percent in April, 48 percent in July and 50 percent in October. The sun shines approximately 59 percent of the time in winter, 62 percent in spring, 75 percent in summer and 70 percent in fall (Brensing and Talley, 1956).

The basin is elongated and irregular with an area of approximately 1720 km^2, an axial length of 105 km and a perimeter of approximately 282 km. It has a form factor of 0.16 and a compactness coefficient of 1.86. The topography is rolling to hilly in the eastern three-fourths while it is gently rolling to almost flat in the western fourth. Greatest relief is about 46 m in the eastern third of the basin.

Formations exposed in the basin belong to three geologic periods. The Hennessey, Garber and Wellington formations were laid down during the Permian and are called "Permian red beds" because of their bright red color. The Pennsylvanian is represented by the Vanoss and Ada formations in the eastern part of the basin. Alluvial sands of the Quaternary are present in the stream bed in most of Noble and all of Pawnee County (U.S.G.S., 1954). Aeolian materials derived from wide alluvial bottom lands are common on the uplands (Galloway et al., 1959).

Exposed formations consist of several types of sedimentary rock. The Hennessey formation is composed mainly of shale with some gypsum and lenticular sandstone (U.S.G.S., 1945). It is approximately 198 m thick. Below it lies the Garber formation which consists of alternating red shales and sandstones that are lenticular, generally cross bedded, and interstratified with sandy shale. Total thickness is approximately 183 m (Soil Conservation Service, 1959). The Wellington formation underlies the Garber formation and consists of red shales and interbedded red sandstones. Two members are recognizable. One is the Fallis, a massive, cross bedded, reddish brown sandstone 15 to 23 m thick. The other is the Insect Bed member, a blue-gray blocky shale approximately 23 to 33 m thick. The Garber and Wellington formations are among the most important aquifers in the state (U.S.G.S., 1945). Formations exposed in the basin have a north-south strike and dip to the west at 7.6 to 8.3 m/km (Soil Conservation Service, 1959).

Soils in the western third of the basin belong to the Bethany-Tabler-Kirkland association while those in the central third belong to the Renfrow-Zaneis-Vernon association. Both associations belong to the Reddish Prairie Great Soil Group. Soils in the eastern third belong to the Parsons-Dennis-Bates association of the Eastern Prairie Great Soil Group. The Vanoss-Minco-Yahola association of the Central Reddish Prairie Great Soil Group forms a narrow strip adjacent to the Arkansas River in the far eastern part of the basin (Gray and Galloway, 1959).

The vegetation of Black Bear basin was sparse to open in the western half while dense stands of trees populated the bottom lands in the eastern half. Post oaks, blackjack oaks and other trees were found on sandy soils while elms, ashes, cottonwoods and willows dominated the alluvial bottom land (Galloway et al., 1959). Native grasses consisted principally of mixed tall and short grasses (Soil Conservation Service, 1959). Croplands predominated in the western two-thirds of the basin; rangelands and pasture made up most of the eastern third.

Source of Brines

Oil wells in this region produce a mixture of oil and brines, which is passed into a mechanical separator where the brines are removed and either stored in an evaporation pit or allowed to escape into a nearby stream. A major source of brines is the Garber oil field, located in the western third of the basin. This field has large numbers of oil wells, tank batteries and separators and many of them are located along Black Bear Creek 24 to 35 km from the origin. Oil installations not included in the Garber field are thinly scattered

TABLE 1

CHEMICAL CHARACTERISTICS OF OIL FIELD BRINES FROM THE GARBER FIELD*

Formation	Resistivity ohms at 26.6 C	Ca ppm	Mg ppm	Na ppm	HCO_3 ppm	SO_4 ppm	Chloride ppm	Total Solids ppm	Date
Crews Sandstone	0.135	3,120	1,050	14,500	17	2,523	29,100	50,310	2/4/54
Ebert Sandstone	0.051	18,800	3,870	83,500	55	456	173,000	279,681	5/31/55
Garber Sandstone	0.043	18,400	3,120	86,000	6	424	174,000	281,950	9/20/53
Hotson Sandstone	0.044	17,200	3,430	82,300	12	375	167,000	270,317	9/21/53
Hoy Sandstone	0.043	18,800	3,510	84,900	73	455	174,000	281,738	2/4/54
Layton Sandstone	0.045	19,600	2,640	66,100	49	446	144,000	332,835	2/4/54
Mississippi Limestone	0.055	11,000	1,420	49,100	24	285	99,300	161,229	8/2/53

*Determinations made by Wright et al. (1957).

along the main channel to 65 km downstream. A few wells are also located near small tributaries that join the main channel along this reach.

Brines from several of the producing formations in the Garber field have been analyzed and were found to be relatively high in ions other than chloride, particularly calcium, magnesium, sodium and sulfate (Table 1). Neither H_2S or $CO_3^=$ was present in the brines while 68 ppm of Ba-Sr was reported for the Ebert sandstone (Wright et al., 1957).

Effluent from a refinery engaged in manufacturing butane and propane gas enters Black Bear Creek 30 km below its origin. The effluent consists primarily of cooling tower blowdown which passes through two small ponds. Brines from nearby oil wells join the plant effluent as it flows to Black Bear Creek.

TABLE 2

CHEMICAL COMPOSITION OF COOLING TOWER EFFLUENT FROM A REFINERY LOCATED NEAR BLACK BEAR CREEK, MARCH 1965

pH.	6.8
Chloride (ppm).	425
Total hardness (ppm).	335
Total alkalinity (ppm).	44
Phenolphthalein alkalinity (ppm).	0
Calcium (ppm)	66
CrO_4 (ppm)	100
Specific conductance (micromhos).	3693

Description of Stations

Eight stations were selected for study. Seven were located along the main channel of Black Bear Creek, and an eighth was located on a small tributary near its confluence with the main channel. Stations were designated by numbers corresponding to distance in kilometers below the stream origin. Stations 22, 43, 46 and 43a had few trees along the banks. Station 65 had moderate tree cover while banks at the remaining stations were thickly lined with trees. Plant detritus was most abundant in the stream bottom at the three lower stations. Moderate entrenchment had resulted in steep banks at all stations. Greatest downcutting had occurred at the three lower stations.

Stream sediments ranged from cobble to silt in size. Silts and fine sands were found in marginal areas of pools. Coarse sand occurred in mid-pool areas. Riffle areas consisted of coarse sand and pebbles except for Station 125 where cobbles were present. Riffle and pool areas of Stations 43 and 46 consisted of coarse sand. The riffle area of Station 125 was located on bed rock.

Stream discharge and depth varied throughout the year (Table 3). Riffles were sometimes absent from the two upper stations but pools persisted even during driest parts of the year. Generally, riffles were abundant in the upper reaches while pools dominated the lower stretches. Maximum depth observed was 1.5 m. Stream discharge increased downstream and was maximum at Station 125. Depth generally increased downstream but was maximum at Station 100. Velocity varied from station to station and was correlated with stream width, the more narrow stations generally having the greatest velocity.

TABLE 3

MEAN ANNUAL STATION CHARACTERISTICS*

Station	Width (m)	Depth (m)	Velocity (m/sec)	Discharge (m^3/sec)
22	1.1	.09	.24	.02
43	2.3	.10	.45	.06
43a	1.0	.06	.03	.01
46	5.9	.21	.09	.10
65	3.7	.22	.23	.23
81	3.3	.26	.41	.32
100	4.5	.42	.19	.48
125	13.5	.33	.10	.54

*Measurements taken from riffle areas.

Eighty-seven flood control reservoirs are to be built on tributaries located in the western two-thirds of Black Bear Creek drainage basin. Thirty reservoirs had been completed at the time this study was made. Stand pipes in each reservoir allow impounded water to flow out gradually, and stream flow was considerably above normal for an extended period of time after heavy rains.

CHAPTER III

PROCEDURES

Physico-Chemical

Water samples were taken from pools at each station on three occasions during each season. Temperature, phenolphthalein alkalinity, methyl orange alkalinity, and pH were measured in the field. Stream discharge was estimated by the method of Robins and Crawford (1954). Turbidity, conductivity and dissolved oxygen samples were analyzed in the laboratory. Water and air temperature were measured at each station with a mercury thermometer. Phenolphthalein and methyl orange alkalinity were determined by titration with .02 N H_2SO_4 (A.P.H.A., 1960). Hydrogen ion concentration was determined by use of a Hellige pH comparator. Turbidity was measured with a Bausch and Lomb Spectronic 20 Colorimeter and conductivity with an Industrial Instruments Conductivity Bridge. Two 126 ml dissolved samples were taken at each station and fixed by the Alsterberg (Azide) modification of the Winkler method (A.P.H.A., 1960). Each sample was titrated with .016 N sodium thiosulfate.

Size of stream bottom sediments was determined with U.S. standard sieves of mesh size 1.98 mm to 0.061 mm.

Biological

Bottom samples were taken at the same time as physico-chemical data. An Ekman dredge was used to collect two bottom samples each from pools and pool margins and two riffle samples were taken with a Surber sampler at each station except 43a and 46.

Species Diversity

Estimates of community structure were obtained with Patten's (1962) equations:

$$H = \sum_{i=1}^{m} n_i \log \frac{n_i}{N}$$

$$\bar{H} = \sum_{i=1}^{m} \frac{n_i}{N} \log \frac{n_i}{N}$$

$$H_{max} = \log N! - m \log (N/m)!$$

$$H_{min} = \log N! - \log \left[N - (m - 1)\right]!$$

$$R = \frac{H_{max} - H}{H_{max} - H_{min}}$$

where (N) is the total number of organisms, (ni) number of individuals per species, (m) number of species in a unit area, (H) community diversity, ($\bar{H}$) diversity per individual, (Hmax) maximum diversity, (Hmin) minimum diversity, and (R) redundancy. Base 2 logarithms are used.

Additionally, indices of diversity and heterogeneity were obtained by using the following equations (Margalef, 1951; 1956b):

$$d = \frac{m - 1}{\ln N}$$

$$IH = d\ (A+B) - \frac{d\ A + d\ B}{2}$$

where (d) is a diversity index, (m) number of species in a given area, (N) total number of organisms, (IH) index of heterogeneity, (dA) diversity index at station one, and (dB) diversity index at station two. The diversity index is derived from the linear relationship between number of species and logarithm of total individuals and is used for computing the index of heterogeneity.

Calculations were performed on an IBM Type 1410 data processing machine at the Oklahoma State University Computing Center.

CHAPTER IV

RESULTS AND DISCUSSION

Physico-Chemical Conditions

Water temperature was generally lower at Station 22 and higher at Station 125 (Table 4). Most of the variation between stations was attributed to shading by trees and to sampling order. The maximum range for any one day was 10 C while the maximum range for any one season was 21 C. Maximum water temperature was 34 C in June 1964 and the minimum was 2 C in January 1964.

TABLE 4

MEAN SEASONAL WATER TEMPERATURE (C)

	Station							
Season	22	43	43a	46	65	81	100	125
Fall	12.0	15.0	14.7	14.3	15.0	14.7	14.3	14.7
Winter	2.8	2.9	2.9	3.1	4.5	4.7	4.7	4.9
Spring	22.0	22.7	22.3	23.7	25.0	24.0	23.0	23.3
Summer	22.6	26.0	26.0	27.3	26.3	26.0	27.0	28.3

Rainfall occurred irregularly throughout the year. Precipitation was maximum in August 1964 when 23.5 cm fell. The daily maximum of 9.3 cm also occurred during August 1964. The minimum amount for any month was 1.4 cm in December 1963.

Maximum stream discharge occurred during summer (Table 5). Winter discharge generally exceeded spring discharge even though rainfall records indicate greater precipitation during spring (United States Department of Interior, Water Resources Division, 1963-64). The difference may have been due to lower evaporation, greater soil moisture and frozen soil with greater runoff in winter. Mean flow for the year at a gauging station 2 km below Station 125 was 2.0 m^3/sec with a maximum discharge of 45.9 m^3/sec 28 August 1964. No flow was recorded on six separate days in July 1964 (United States Department of Interior, Water Resources Division, 1963-64).

TABLE 5

MEAN SEASONAL DISCHARGE (M^3/SEC)

	Station							
Season	22	43	43a	46	65	81	100	125
Fall	.03	.09	.01	.09	.21	.25	.35	.37
Winter	.02	.07	.02	.14	.18	.24	.43	.44
Spring	.01	.03	-	.04	.13	.27	.34	.39
Summer	.01	.12	-	.12	.46	.54	.78	.88

The montmorillonite clay which was the principal source of turbidity in Black Bear Creek possesses distinct physical properties. The particles are flattened and disc shaped (Irwin and Stevenson, 1951). They have an electrical double layer consisting of a net negative or net positive charge with an equal ionic charge in the liquid near the particle surface (van Olphen, 1963). Under stable conditions, clay particles are attracted to one another by van der Waals forces. The attractive forces may be counteracted by electrical repulsion. The magnitude of these forces depends on the concentration of ionized compounds. At low electrolyte concentration, ions in the medium diffuse away from the particle to areas of low concentration resulting in a less dense atmosphere of ions around the particle. Conversely, higher electrolyte concentration results in considerable compression of the atmosphere of ions toward the particle. Ions with a higher valence give a more pronounced compression. At high ionic concentration, electrical repulsive forces cannot counteract van der Waals forces, thus aggregation and precipitation of particles occurs.

In general, turbidity decreases as conductivity and hardness of water increases (Esmay et al., 1955; Keeton, 1959). Irwin (1945) and Irwin and Stevenson (1951) precipitated clay particles in ponds by increasing the pH. Esmay et al. (1955) found that addition of gypsum to turbid ponds aided in flocculation and precipitation of clay particles. Calcium, magnesium and sodium were present in high concentration in some reaches of Black Bear Creek and aided the precipitation of clay particles.

An experiment was conducted in which turbid pond water and brines from the Garber oil field were mixed at various concentrations (Fig. 3). Initial conductivity at 23 C was 59,000 micromhos for the brines and 208 for the pond water. Flocculation and precipitation occurred at various rates but was most rapid at higher brine concentrations. Keeton (1959) utilized this method to clear farm ponds in Oklahoma. Treated ponds remained clear even after heavy rainfalls caused increased turbidity in other ponds located in the same region.

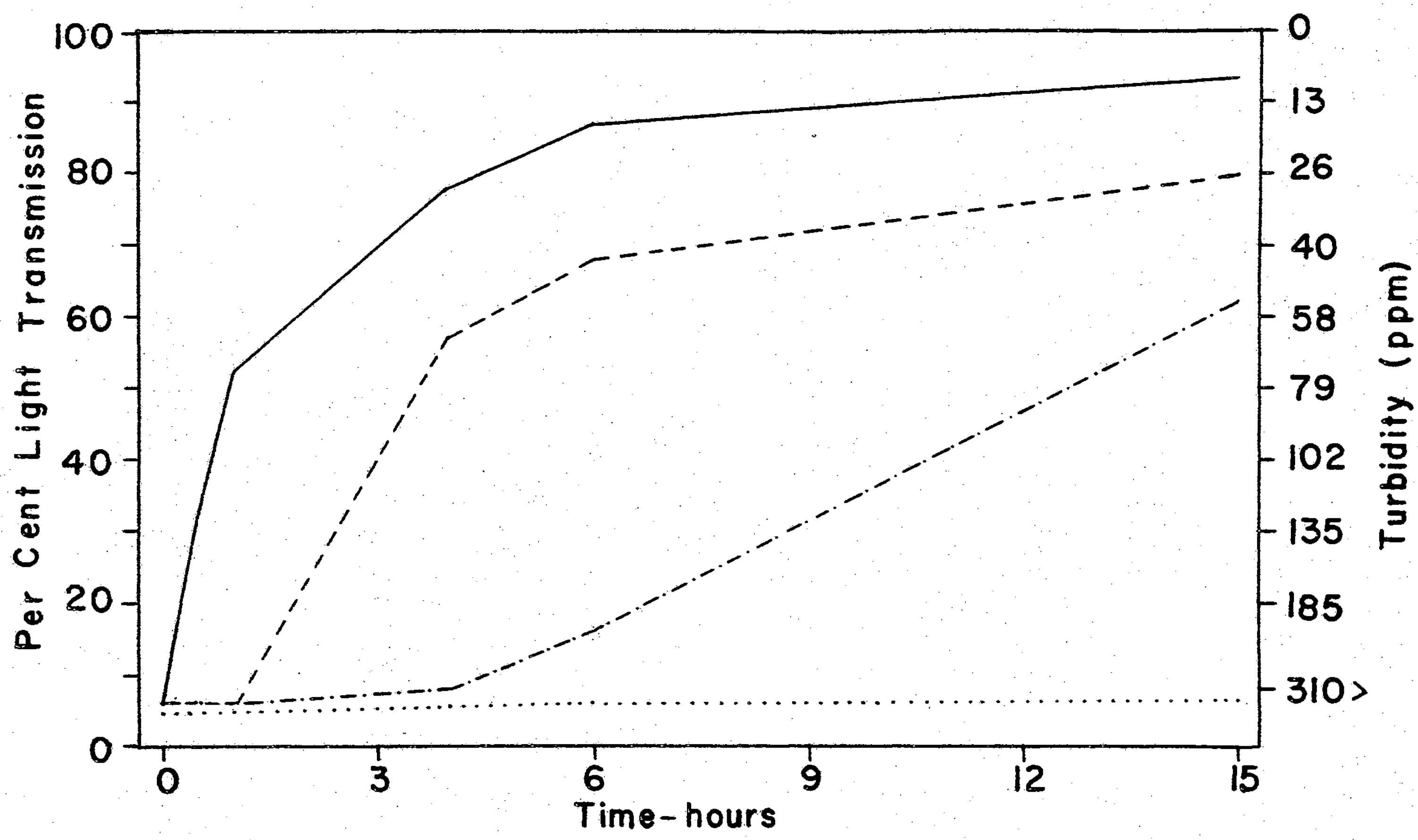

Fig. 3. Precipitation of clay particles in pond water by oil field brines. Twenty parts pond water - one part brine = (—); 100 parts pond water - one part brine = (-.-); 200 parts pond water - 1 part brine = (- - -); pond water only = (. . . .). Measurements determined with Spectronic 20 at D_{450}.

Generally, turbidity in Black Bear Creek was highest during spring and summer and lowest in winter (Fig. 4). High turbidity was caused by increased flow and dilution. Low turbidity at all stations during winter was attributed to increased ion concentration, decreased precipitation and decreased turbulence.

Seasonal variation in conductivity was much less extreme than longitudinal variation (Fig. 5). Conductivity below the brine influx ranged from 231 micromhos at Station 125 to 16,000 micromhos at Station 43. Greatest range among stations on any day was 14,910 micromhos. Conductivity at unpolluted Stations 22 and 43a were similar and ranged from 240 to 1,297 micromhos during the year. Higher conductivity during winter may be attributed to a more uniform distribution of brines downstream as a result of infrequent precipitation and slight fluctuation in stream discharge. Heavy rains in other seasons flushed the brines out of the stream leaving only Stations 43 and 46 with a high specific conductance.

At Station 22, above the brine influx, turbidity decreased and conductivity increased during winter. This natural increase in conductivity may be attributed to leaching of soluble salts from surface formations during periods of low, steady flow and to infrequent precipitation. When rains occurred more frequently during other seasons, dissolved salts were flushed downstream and conductivity was lowered.

Conductivity decreased and turbidity increased downstream because of dilution by water entering the stream from brine-free tributaries. Turbidity at all stations was higher and conductivity lower after heavy rain in the basin. Mean annual values for turbidity and conductivity are similar to seasonal values (Fig. 6).

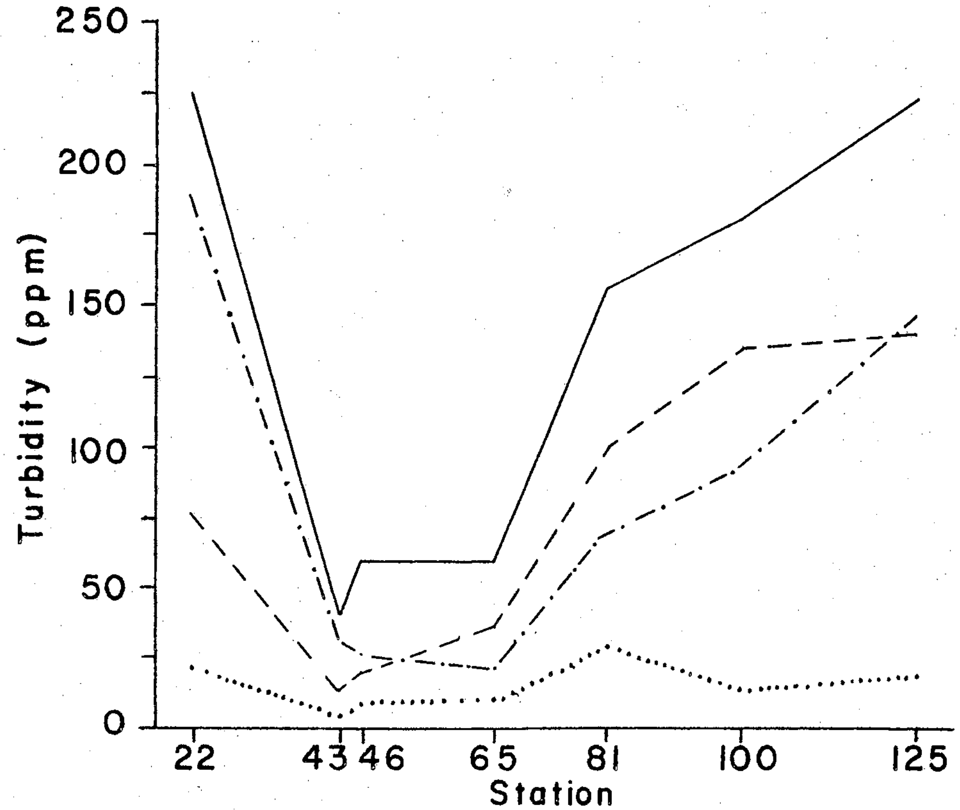

Fig. 4. Mean seasonal turbidity. Fall = (—·—), winter = (·····), spring = (– – –), summer = (——).

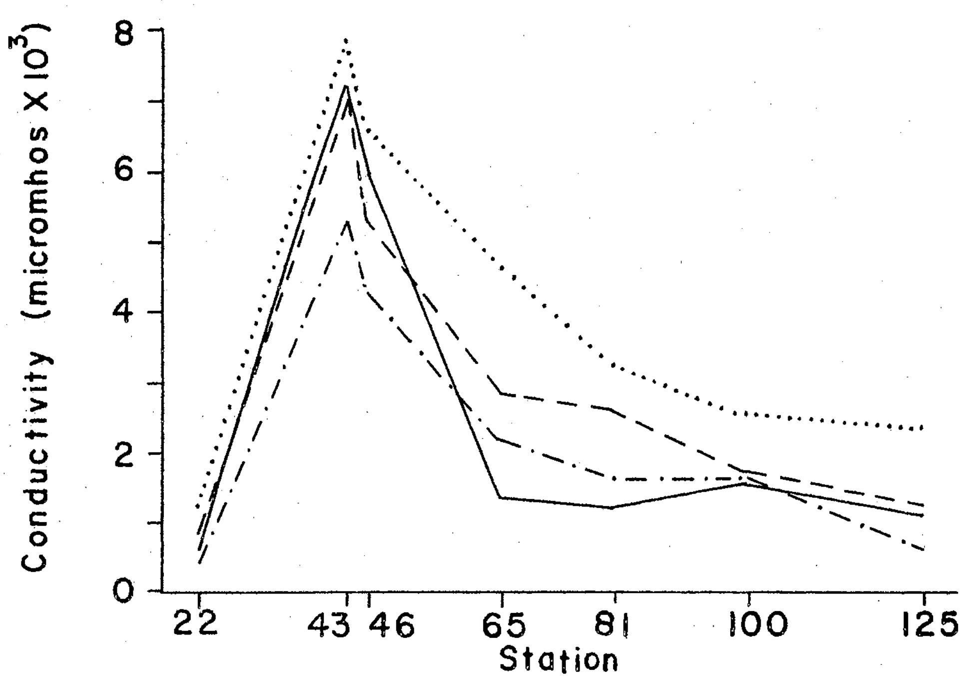

Fig. 5. Mean seasonal conductivity. See figure 4 for code.

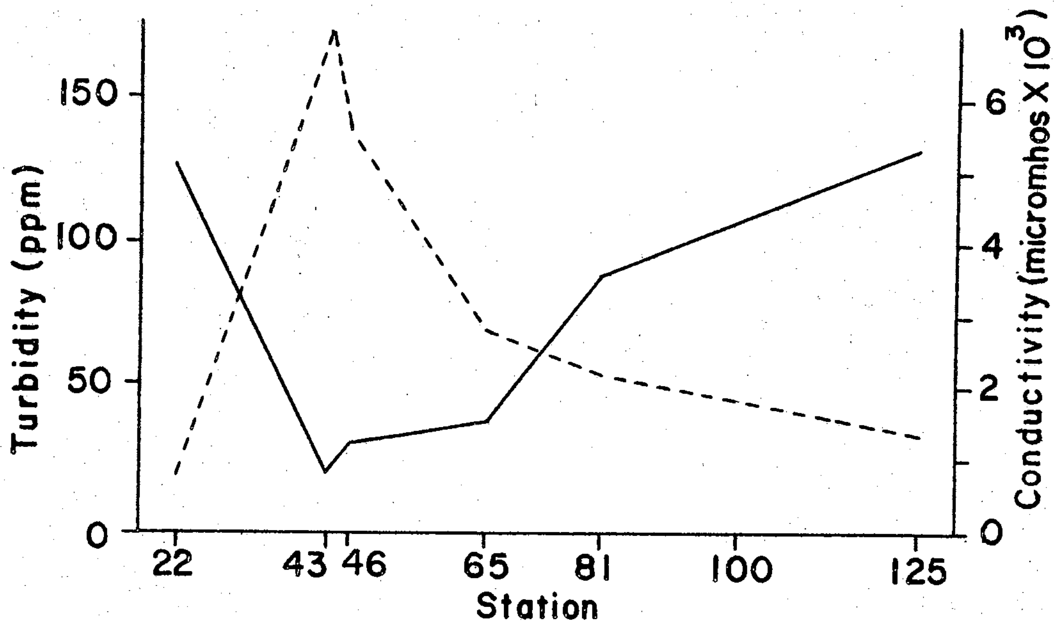

Fig. 6. Mean annual turbidity and conductivity. Conductivity = (- - -); turbidity = (——).

Measurement of specific conductance is a means of detecting brine and acid pollution produced by water from oil wells (Ellis, 1937). Specific conductivity of a stream supporting a well developed fish fauna should range between 150 and 500 micromhos at 25 C. Some western waters in alkaline regions normally have high specific conductance up to 2,000 micromhos. Pollution may exist if conductivity exceeds 1,000 micromhos in non-alkaline regions and 2,000 micromhos in alkaline regions. Clemens and Finnell (1955) reported specific conductance of 1,570 to 2,070 micromhos at 18 C for portions of the Little Washita River in gypsum deposits. Salt Creek, a brine polluted stream located in the same region, exhibited specific conductance of 4,800 to 42,100 micromhos at 18 C.

Chloride concentration in Black Bear Creek was not measured during this study, but was assumed to vary with specific conductance. Tarzwell (1956) indicated that the chloride ion is not a reliable index of osmotic strength when dealing with a mixed salt solution such as oil field brines. He concluded that the cations are of greater importance as a toxic agent to aquatic life and that the chloride ion is of little significance.

Oxygen concentration measured during daylight hours ranged from 44% saturation (3.7 ppm) at Station 22 to 140% saturation (12.1 ppm) at Station 125 (Table 6). Some variation among stations was due to sampling order and amount of tree cover. In many streams, 3 to 5 ppm of oxygen is considered the lowest limit which many forms of life can tolerate over a long period of time while as little as 2 ppm may be tolerated over short periods of time (Patrick, 1962).

TABLE 6

MEAN ANNUAL PHYSICO-CHEMICAL CONDITIONS

Station	Temperature C	Oxygen % Sat.	Alkalinity HCO_3^- ppm	Alkalinity $CO_3^{=}$ ppm	pH
22	14.7	73	209	5	8.1
43	16.7	93	136	4	8.1
43a	16.4	78	256	8	8.1
46	17.1	93	155	1	8.1
65	17.6	94	200	4	8.1
81	17.5	87	225	2	8.0
100	17.2	87	221	4	8.0
125	17.8	98	182	14	8.2

Methyl orange and phenolphthalein alkalinity exhibited a wide range throughout the year. Methyl orange alkalinity as $CaCO_3$ equivalent ranged from 70 to 355 ppm. The range among stations on any day was 160 ppm. Mean annual methyl orange alkalinity in Black Bear Creek was highest at Station 81 and lowest in reaches with high brine concentration. Methyl orange alkalinity in the unpolluted tributary ranged from 79 to 534 ppm throughout the year. This was the maximum range for any station. Low methyl orange alkalinity consistently observed at Stations 43 and 46 resulted from precipitation of carbonate as $CaCO_3$ or $MgCO_3$. Maximum phenolphthalein alkalinity range among stations on any day was 100 ppm. Mean annual values were lowest at Station 46 and highest at Station 125. Low mean annual methyl orange alkalinity and high phenophthalein alkalinity at Station 125 was accompanied by a slight increase in pH and decrease in Mg^{++} and Ca^{++}. Streams with methyl orange alkalinity above 100 ppm are more productive than those with low methyl orange alkalinity (Tarzwell, 1936).

Hydrogen ion concentration ranged from 7.6 to 8.6 during the year. Mean annual values were minimum at Stations 81 and 100 and maximum at Station 125. Only slight seasonal fluctuation occurred except for somewhat lower values during the fall. A pH range from 6.5 to 8.5 is to be expected in most fresh water streams (Ellis, 1937).

Biological

Seventy-nine species in 74 genera and 10 orders were collected (Table 7). Nearly a third of the species (30%) were tendipedid dipterans.

TABLE 7

AVERAGE NUMBERS OF BENTHIC MACROINVERTEBRATES PER M^2

Station	22				43				65				81				100				125			
Season	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S
DIPTERA																								
Paralauterborniella nirgrohalterale											6					45								
Procladius sp.	1		8				2				1	10				1	1		2		2			
Pelopia sp.		1	8	2			10	3				39				2								29
Glyptotendipes lobiferus?										2	1	2	1	2	2	7	1		1	2	5	2		2
Polypedilum halterale	1	1										11				4								
Pseudochironomus fulviventris				11					2	7		1				7							1	
Stenochironomus sp.										1							2	2					1	
Tendipedini sp.														1					2				8	
Corynoneura nr. xena	22						2		4		5			2							3	14		
Ablabesmyia mallochi												6									2			
Tanytarsus nr. nigricans									1				4	1	1	1			2	4	2		37	
Cryptochironomus sp.	14	11	29	4			4	2	20	13	41	11	10		13	23	19	14	17	8	22	43	29	11
Tanytarsus sp.		5																						
Cricotopus bicinctus		41																						
Polypedilum nr. scalaenum	5				34	6	104	57	17	14	23	41	23			31	2		10		45	4	54	26
Hydrobaenus nr. dorenus	38	853	261		6	11	104		164	853	7	1	1	103	1	7	1	104	6		2	125	5	
Tendipes modestus	4	208	20		178	5	4	86	55	182	29	176		26	1		1			11	3	4	7	98
Hydrobaenus nr. nivoriundus		56				6				1154				79	64		2	304			3	536	5	2
Calopsectra nr. exigua	1	72	35	2	181		39		258	23	8	511	426	11	71		224	18	7	7			5	26
Pentaneura sp.	14	97	43	15	23	24	23	20	102	225	152	258	72	94	54	212	54	98	91	35	38	32	177	88
Polypedilum illinoense?			29				2		32	14	13	91	152	100	178	313	184	19	234	94	12		66	5
Metriocnemus? sp.										27				36			97	1				214		3
Tendipes nr. riparius	1	2					2			81	7	212			1			1	1			2		6
Simulium vittatum	163	8615	683	224	15	66	8	12	859	8925	41	19	950	4839	25		3698	7663	96		28	824	14	
Culicoides sp.	1	1						1	8	4	11	2											1	2
Ceratopagonidae sp.		1	18			1	22		20	2	11	11			1	8		1		11	2	8		5
Hemerodromia sp.										1	6		2		8	7	2		11				4	
Limnophora sp.											2				3			1				2	2	
Tabanus sp.	4	4								1														
Cecidomidae sp.														5										
Erioptera sp.	25	19			23	19	44	5	10	5	2	5		1		1								
Tipula sp.						1																		

TABLE 7 (Continued)

Station	22				43				65				81				100				125			
Season	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S
COLEOPTERA																								
Heterelmis sp.			2											2	2	1							22	
Stenelmis sp.			2			2			1		1	17	4	2	22	38	17	6	30	56	15	13	85	112
Dubiraphia sp.	2	1	6			2														1				2
Helichus sp.			2					2				2	1			14	11		24	14	11	1	1	2
Berosus sp.	2	2	3		2							1				2							4	
Hydrophorus sp.												2												
Peltodytes sp.			2	4																				
Enochrus sp.												9				1								
Cymbiodyta sp.												5												3
Hydrochus sp.												2												
Helophorus sp.												1												
Tropisternus sp.																1								11
Dineustis sp.																1		2				4	1	
Cyphon sp.																1							1	5
Dytiscidae sp.		10	2																					
EPHEMEROPTERA																								
Baetis sp.	2	4							14		32	31	7		31	14	19	27	43	6	5	1	25	14
Hexagenia sp.	4	2			1							1						1			1	4	1	
Caenis sp.	185	153	633	32	58	14	8	1	7	7	18	774	25	1	19	163	44	4	13	13	43	5	195	69
Stenonema sp.		5	14	4				2	45	49	20	263	84	11	129	96	139	43	153	30	194	8	86	58
Paraleptophlebia sp.									17	35	1	27		5			1			1				
TRICHOPTERA																								
Potamyia flava									5	5	4	6	6	1	2	2	7	5		1	3	5	11	
Athripsodes sp.																						2	7	
Leptocella sp.																							2	
Oecetis inconspicua												6												
Cheumatopsyche sp.	4	1	20	2	2		1		340	133	81	4152	409	155	30	666	985	609	713	1463	69	47	769	8
Hydropsyche sp.					17						5		7	18	1	80	85	31	928	315			36	

TABLE 7 (Continued)

Station	22				43				65				81				100				125			
Season	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S
ODONATA																								
Argia sp.	1	1				2					1		2		1	1	2	7	7	4	22	1	25	18
Gomphus sp.				11						1	2	8	1			1		1			2	5	1	2
Hetaerina sp.	4															1			2	6	2			2
Progomphus obscurus					5	2	1																	2
Libellula sp.																								2
Macrothemis sp.				2												1								
Erpetogomphus sp.												4												
Nehallenia sp.								1																
Macromia sp.				13																				
Perithemis sp.				9																				
NEUROPTERA																								
Corydalus cornutus															98		22		7	54	2		11	5
Sialis sp.																								1
HEMIPTERA																								
Trichocorixa sp.												1				172	1			6			1	2
CRUSTACEA																								
Hyalella azteca	11	8	22	2																				
MOLLUSCA																								
Physa anatina				2								27					1	5	8				6	
Sphaerium transversum	24	50														2	1	11	83	62		8	57	
Ferrissia shimeki	1	1																			3			3
ANNELIDA																								
Limnodrilus sp.	220	116	135	52	18	1	6	2	6	27	32	77	24	48	47	48	32	59	18	75	6	66	35	65
Branchiura sowerbyii													1	2	56	50	8	6	38	59	6	7	36	35
Glossiphonia sp.				4																				
Helobdella sp.				1																				

Distinct differences in species composition were found above and below the source of brines. During the year, 55 species were collected from Station 125 where brine concentrations were relatively low. Above the outfall, 47 species were collected. The smallest number of species, 31, was found at Station 43 located just below the outfall.

Seasonal variation in numbers of species and faunal composition was evident. Maximum numbers of species occurred during summer in middle reaches and during spring in lower reaches (Fig. 7). In general, the number of species present at each station increased downstream during all seasons except summer.

Some species apparently were excluded from middle reaches of the stream by high brine concentrations. Nine species were collected only at Station 22, above the brine influx, while two species were found only at Station 125. One of the nine species found only at the unpolluted station was Hyalella azteca, an animal generally associated with unpolluted waters (Pennak, 1953). Ferrissia shimeki was the only species collected from the upper unpolluted station and Station 125.

Evidence that oil field brines may be limiting to certain species comes from a comparison of the faunal composition of Black Bear Creek and one of its brine free tributaries, Camp Creek, located in the eastern third of the basin. During the summer of 1964, benthic macroinvertebrates were collected from 15 stations in Camp Creek basin. Maximum conductivity did not exceed 650 micromhos at 23 C. At some stations in Camp Creek, Sphaerium transversum reached a density of $1300/m^2$. This animal was absent from the middle reaches of Black Bear Creek where brine concentrations were high. Other organisms such as

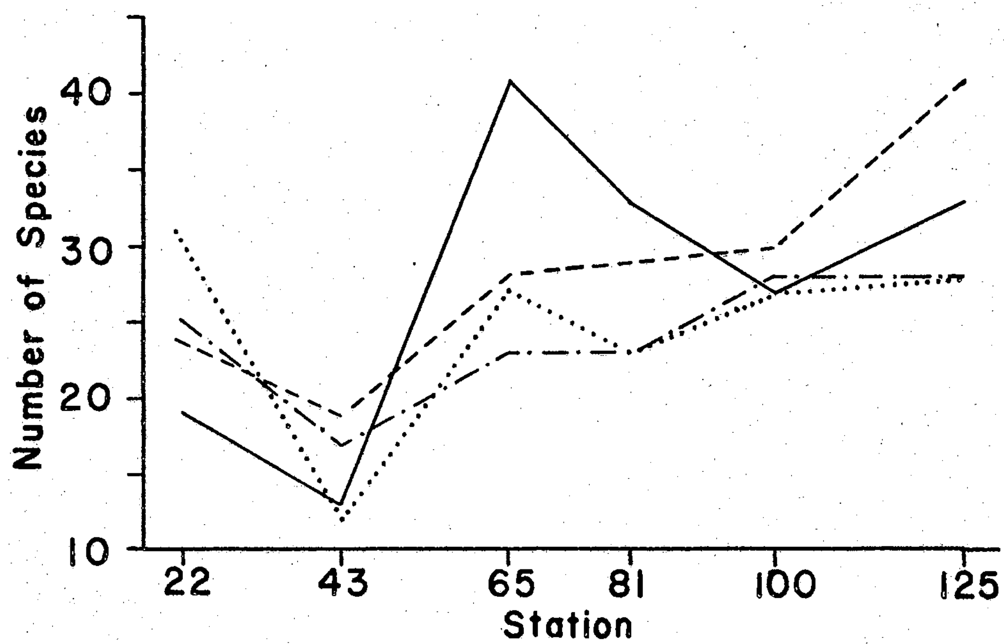

Fig. 7. Seasonal variation in numbers of species. See figure 4 for code.

mosquito larvae, phantom midges, alderflies and leeches were abundant in Camp Creek but were rare or absent in Black Bear Creek.

Some investigators have considered that certain associations of organisms indicate presence or absence of organic pollution. Populations of mayflies, stoneflies and caddis flies in general denote clean water conditions while their absence is indicative of pollution as long as the habitat is suitable (Gaufin and Tarzwell, 1956). Stoneflies were not found in the brine-polluted Black Bear Creek, but mayflies and caddis flies were abundant, especially at the four downstream stations. Only one species of mayfly was abundant at the unpolluted station.

In southern Oklahoma only a few species were found in areas where brine concentration was high (Clemens and Finnel, 1955). The average number of organisms ranged from four at chloride concentrations between 13,000 and 20,000 ppm, to 13 below 1,000 ppm. Tendipedids were the only benthic macroinvertebrates found at the highest concentration; dragonflies occurred in intermediate concentrations, and *Physa* sp. was present at the lower concentrations. Maximum conductivity was 42,100 micromhos at 18 C, considerably higher than in Black Bear Creek.

Relative resistances of some benthic macroinvertebrates to brine wastes were determined by Clemens and Jones (1954). In order of decreasing resistance the animals were dragonflies (Libellulidae and Coenagrionidae), *Hexagenia* sp., Tubificidae, *Hyalella* sp., Baetidae and *Physa* sp. None of these organisms were abundant in Black Bear Creek.

Oil field brines in Black Bear Creek apparently are not as harmful to benthic organisms as are domestic and oil refinery effluents. Only 42 species of benthic macroinvertebrates were found in Skeleton Creek (Wilhm, 1965). Species distribution ranged from six at upper stations to 27 at lower stations.

The majority of benthic macroinvertebrates in Black Bear Creek belonged to three families of insects: Tendipedidae, Simulidae and Hydropsychidae (Figs. 8, 9 and 10). During some seasons the three families comprised as much as 99% of the total individuals. Other families combined exceeded 50% of the total once during fall at the unpolluted station and twice at Station 125, once during fall and once during summer.

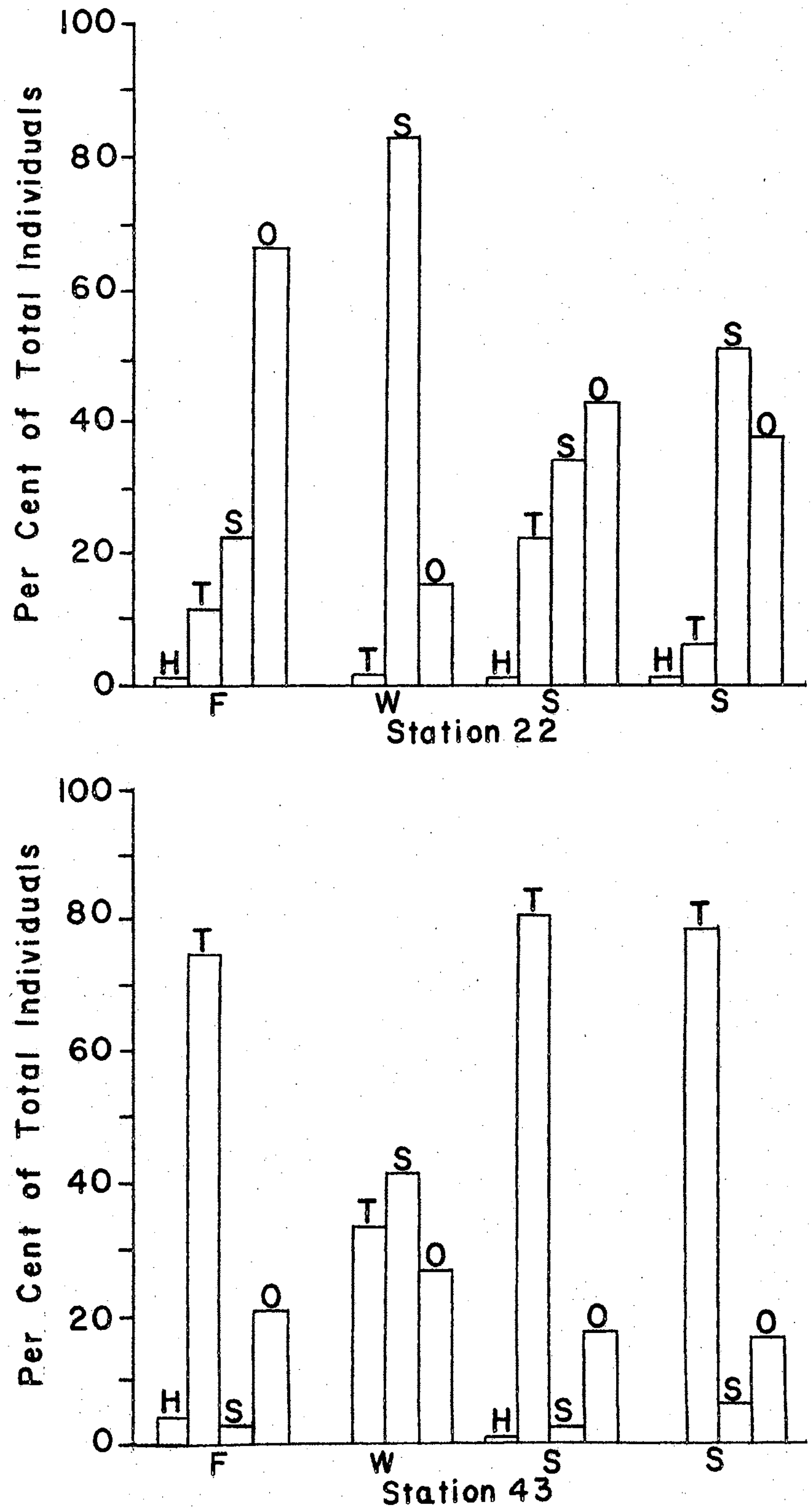

Fig. 8. Seasonal variation by dominant families at two upper stations. Hydropsychidae = H, Tendipedidae = T, Simulidae = S, other families combined = O.

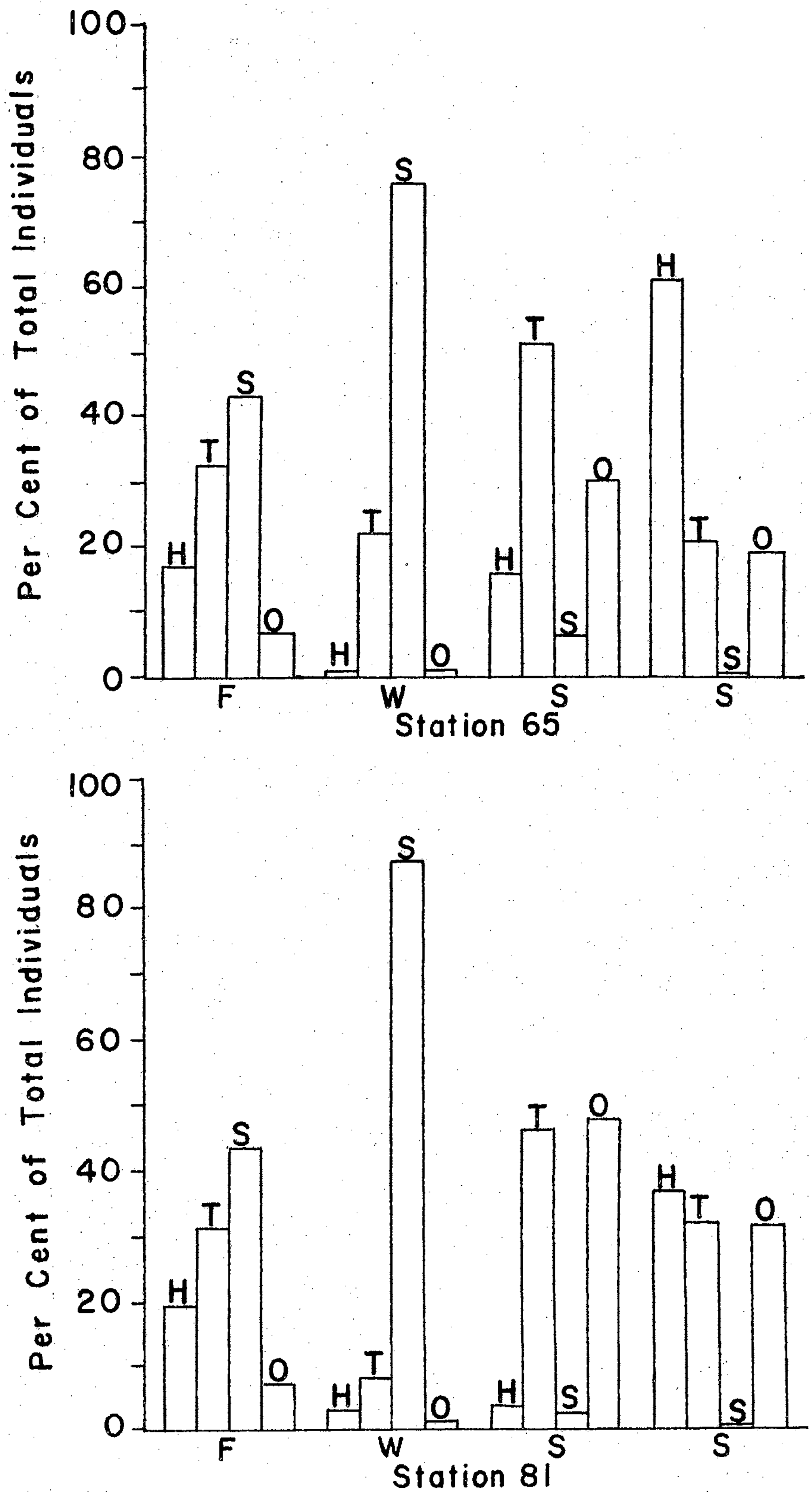

Fig. 9. Seasonal variation by dominant families at two middle stations. Hydropsychidae = H, Tendipedidae = T, Simulidae = S, other families combined = O.

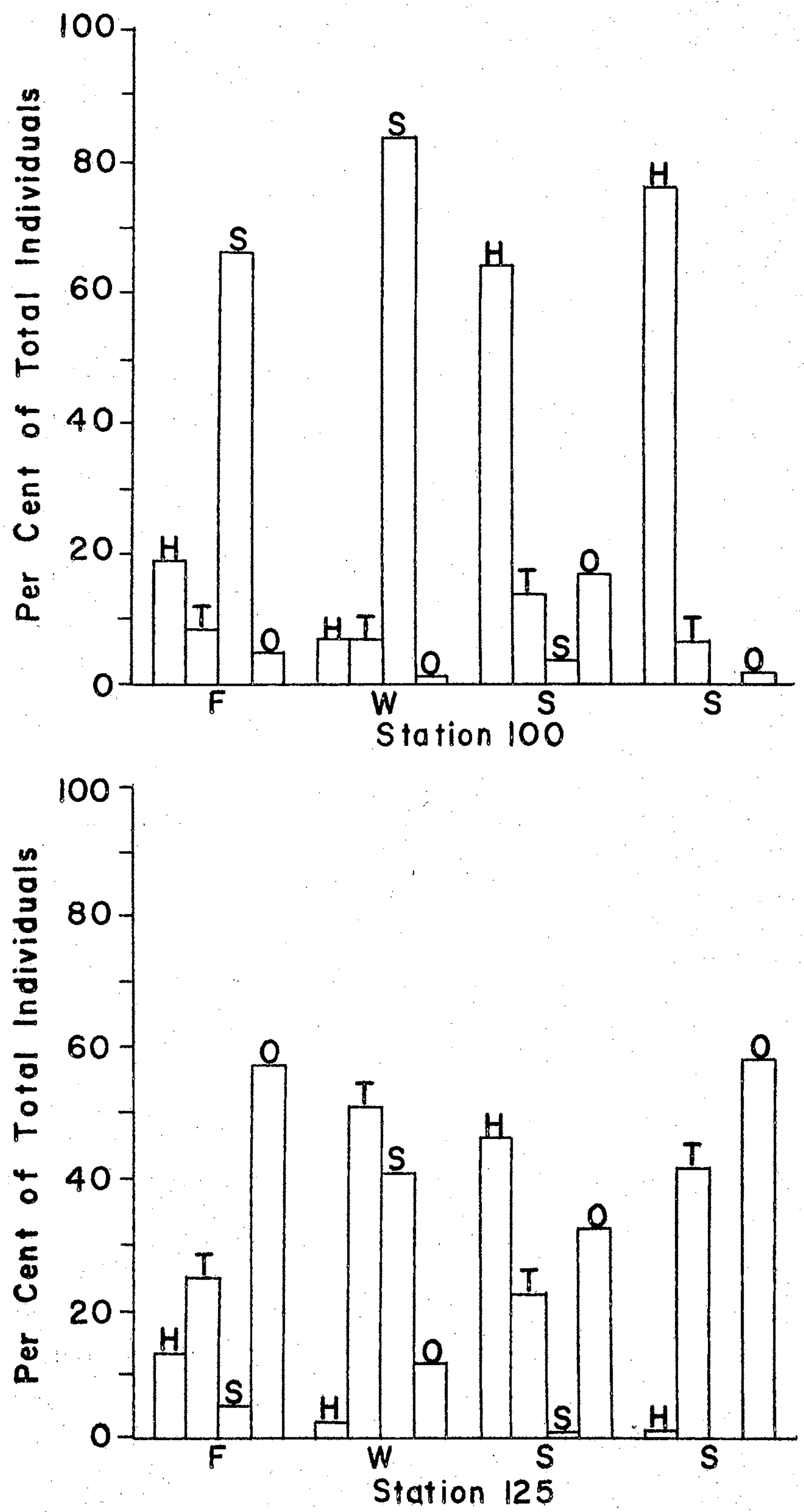

Fig. 10. Seasonal variation by dominant families at two lower stations. Hydropsychidae = H, Tendipedidae = T, Simulidae = S, other families combined = O.

Number of individuals varied among stations as well as seasonally (Fig. 11). Winter was the most productive season at all stations. During this season an average of 11,800 individuals per m^2 occurred at one station. The maximum number in Skeleton Creek was $3{,}560/m^2$ during fall (Wilhm, 1965). Large numbers of Simulium vittatum composed most of the winter fauna in Black Bear Creek. Large seasonal peaks observed during summer at most stations were due to Cheumatopsyche sp.

Longitudinal variation in numbers of individuals and species resulted from seasonal emergence, differences in stream bed composition, turbidity, salinity and drying of riffles at the two upper stations during summer. Increased stream velocity and volume following rains severely reduced populations, especially during spring and summer.

The large numbers of bottom organisms in Black Bear Creek may have resulted from increased primary productivity associated with decreased turbidity and increased light penetration. Algal blooms were noted on several occasions, especially in less turbid reaches of the stream. Benthic macroinvertebrate communities in unpolluted streams of this region have not been investigated, but pond studies show that light penetration is a major limiting factor to productivity. Keeton (1959) used oil field brines to reduce turbidity and increase light penetration in turbid ponds. As a result, production of plankton, some benthic macroinvertebrates, fish and aquatic plants increased. Buck (1956) reported eight times more plankton in clear water than in ponds of intermediate turbidity (25-100 ppm) and 12.8 times more than in ponds of high turbidity. In a comparison of 20 ponds and 20 lakes, Claffey (1955) found largest numbers of plankton in clear water, lesser

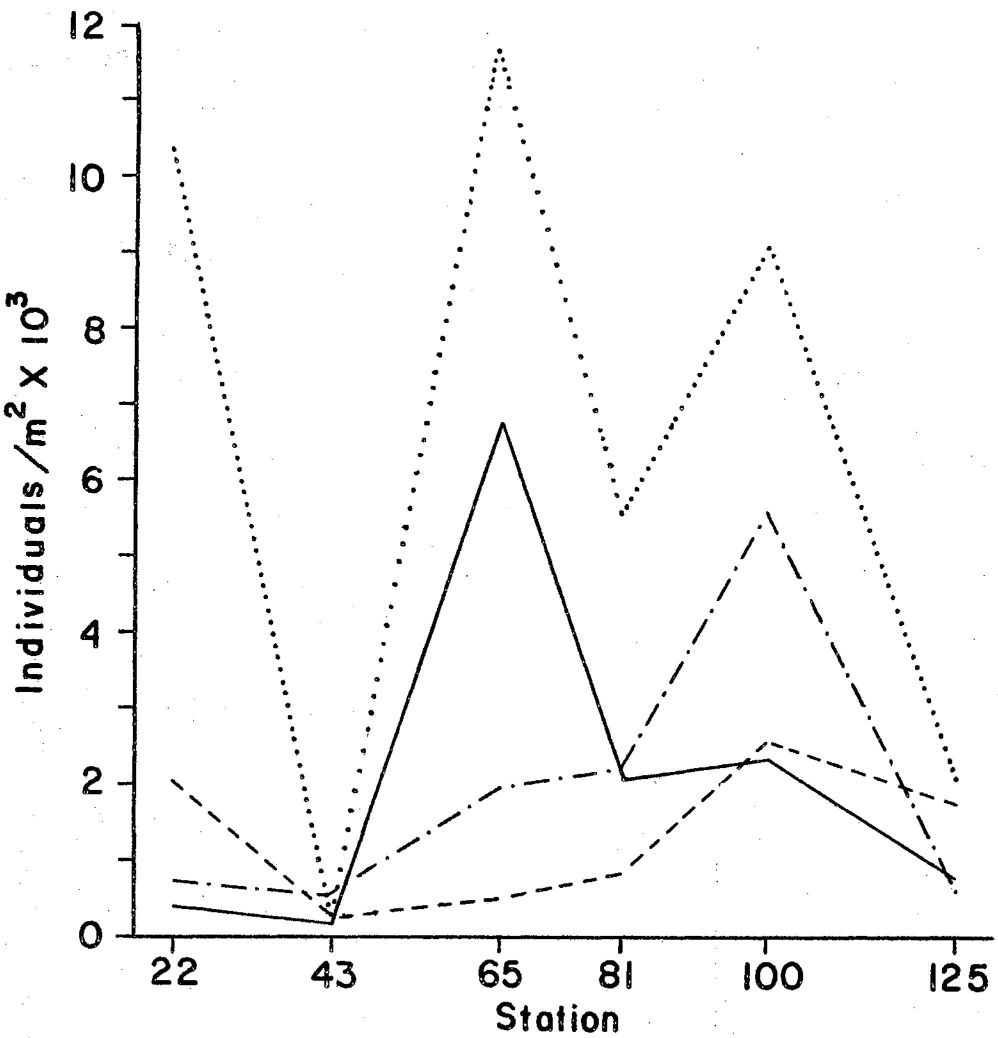

Fig. 11. Seasonal variation in numbers of individuals. See figure 4 for code.

numbers at intermediate turbidity (25-50 ppm) and smallest numbers at higher turbidity. Butler (1964) found that summer productivity in a clear pond (12 g $0_2/m^2$ day) exceeded that in a turbid pond (4 g $0_2/m^2$ day). The ratio of gross productivity to community respiration (P/R ratio) exceeded one in the clear pond but was less than one in the turbid pond.

Indices of Community Structure

Indices obtained by using ideas developed in the field of information theory were used to evaluate community structure of benthic macroinvertebrates in Black Bear Creek. Community diversity (H) reflects the manner in which individuals are distributed among the species in a community and is dependent on the area sampled. Diversity per individual ($\bar{H}$) and redundancy (R), however, are independent of the area sampled. Maximum diversity (Hmax) is calculated by considering each individual as a different species while minimum diversity (Hmin) is calculated by considering all individuals as belonging to a single species. Thus, H is located somewhere between Hmax and Hmin and its position is defined by R (Patten, 1962).

Seasonal and longitudinal variation in the distribution of individuals into species was reflected by H, $\bar{H}$ and R (Figs. 12, 13 and 14). H varied directly with numbers of individuals. As a result, it resembled counts of individuals (Fig. 11). $\bar{H}$ tended to vary inversely with R. R, a measure of the repetitious occurrence of individuals, was high when a few species dominated the community. Maximum R and minimum $\bar{H}$ occurred during winter at all stations except Station 43 where brine concentration was highest. High values for $\bar{H}$ and R during winter were caused by large numbers of <u>Simulium vittatum</u> and several species of Tendipedidae.

In general, annual values for H, $\bar{H}$ and R were similar to seasonal values (Fig. 15). Values in the figure were calculated from numbers of species and individuals collected from each station during the year.

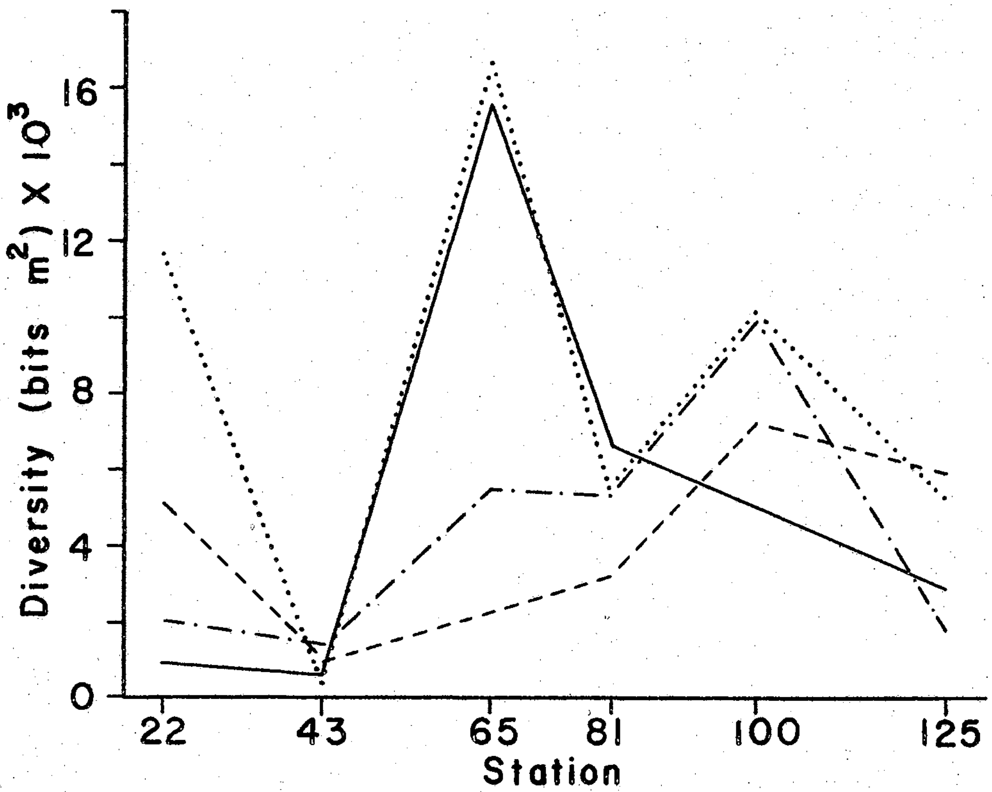

Fig. 12. Seasonal variation in diversity, bits/m^2 (H). See figure 4 for code.

The high annual peak in H at Station 65 was caused by high winter and summer values. At Station 100, high annual H was caused by somewhat similar H at all seasons. Low R and high $\bar{H}$ at Stations 43 and 125 reflected the absence of large seasonal peaks caused by large numbers of one or two species.

Hmax and Hmin are useful principally in calculation of the parameter R. Hmax, considering each individual as a different species, exceeded 50,000 bits/m^2 at Stations 22 and 65 during winter when <u>Simulium vittatum</u> was abundant (Table 8). Hmin, considering all individuals as a single species, was greater than 500 bits/m^2 at

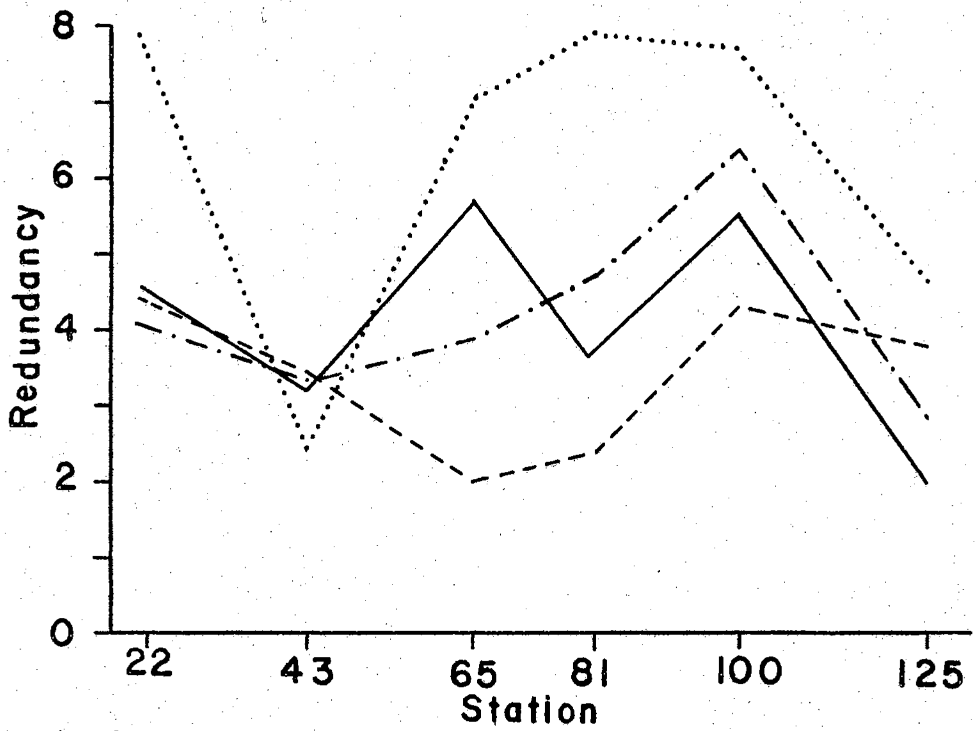

Fig. 13. Seasonal variation in redundancy (R). See figure 4 for code.

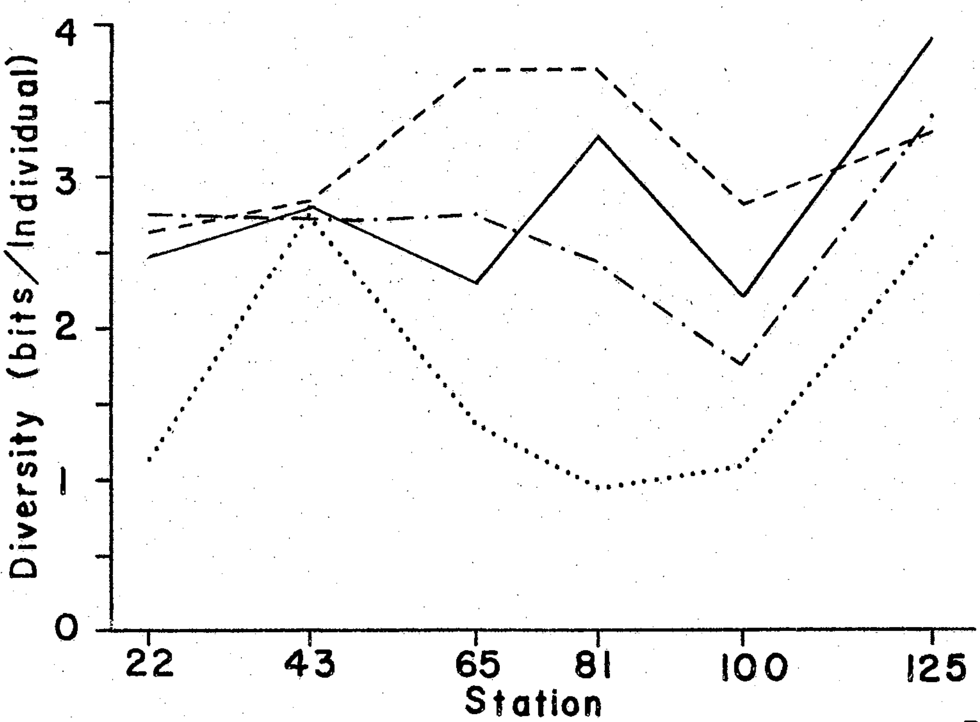

Fig. 14. Seasonal variation in diversity, bits/individual ($\bar{H}$). See figure 4 for code.

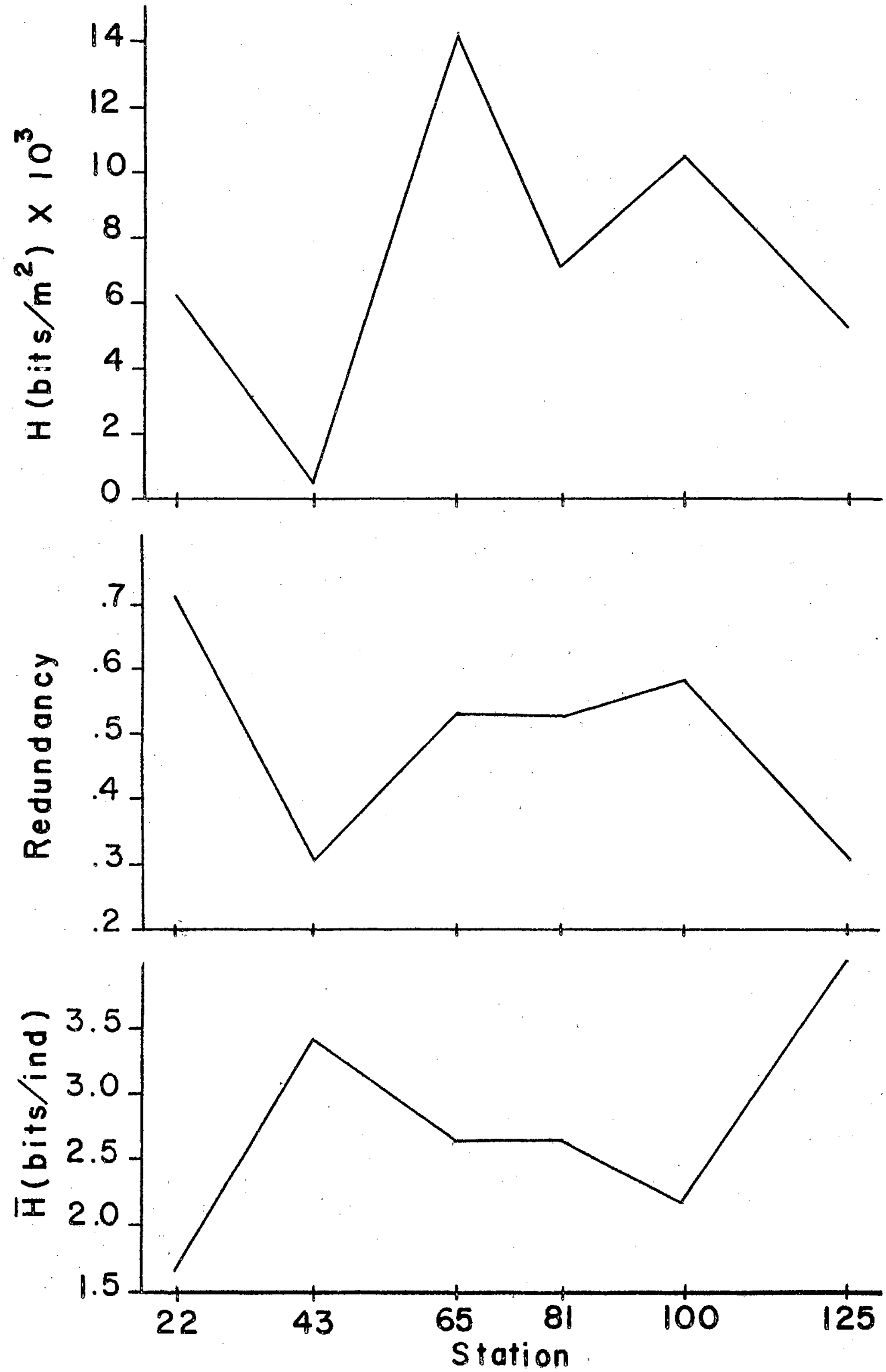

Fig. 15. Annual variation in H, R, and $\overline{H}$.

at Stations 65 and 125 during fall.

TABLE 8

SEASONAL VARIATION IN HMAX AND HMIN

Station	Fall		Winter		Spring		Summer	
	Hmax	Hmin	Hmax	Hmin	Hmax	Hmin	Hmax	Hmin
22	3,237	256	51,282	469	9,105	366	1,561	290
43	2,227	290	543	92	1,495	177	716	130
65	8,972	282	55,995	413	2,546	285	36,255	596
81	9,984	285	24,934	320	4,206	318	10,114	410
100	26,687	393	43,327	401	12,472	383	11,015	340
125	2,471	250	9,571	346	9,283	504	3,497	422

Concise numerical indices of community structure derived from information theory make possible quantitative comparisons of populations of benthic macroinvertebrates in different streams under different conditions. Wilhm (1965) used such a method to describe community structure of bottom organisms in Skeleton Creek, a stream comparable in size to Black Bear Creek, but which receives domestic and oil refinery effluents near its origin. Mean annual values derived from the means of four seasons in Skeleton Creek are compared with Black Bear Creek (Table 9). The two streams differ in that Skeleton Creek receives oil refinery and domestic effluents while Black Bear Creek receives oil field brines.

Comparative mean annual diversity indices show that oil field brines in Black Bear Creek were less restrictive to bottom organisms than effluents in Skeleton Creek. With the exception of R, parameters for Black Bear Creek generally exceeded those in Skeleton Creek. High R in Skeleton Creek was caused by presence of large numbers of three species in the more highly polluted reaches of the stream. Downstream stations in both streams exhibited high $\bar{H}$ and low R reflecting improved stream conditions with a varied and more natural fauna.

TABLE 9

COMPARATIVE MEAN ANNUAL DIVERSITY INDICES

Station*	H (bits/m^2)	$\bar{H}$ (bits/ind)	R	Hmax (bits/m^2)	Hmin (bits/m^2)
Skeleton Creek					
19	929	1.02	.56	2,527	33
30	1,475	.84	.56	3,102	37
35	1,847	.83	.63	5,020	48
54	1,045	1.88	.51	1,901	119
61	638	1.59	.58	1,424	108
82	809	2.43	.44	1,189	132
120	858	3.44	.20	1,061	145
Black Bear Creek					
22	5,016	2.26	.52	16,296	347
43	891	2.79	.31	1,246	152
65	9,995	2.55	.47	26,192	394
81	5,179	2.60	.47	12,301	334
100	8,081	1.98	.60	23,375	379
125	3,986	3.30	.33	6,206	380

*Station numbers correspond to distance in kilometers below the origin for both streams. Skeleton Creek data modified from Wilhm (1965).

Pollution in Skeleton Creek created a more orderly environment by excluding certain species and allowing those that remained to produce large numbers of individuals. As a result, randomness was decreased and less information was required to describe its community structure. Because upstream polluted areas had only a few species and many individuals, R was high and $\bar{H}$ low.

Oil field brines in Black Bear Creek did not limit the number of species to the extent found in Skeleton Creek. High values for H in Black Bear Creek reflected faunal assemblages that more closely resembled natural communities. As a result, a greater amount of randomness in Black Bear Creek required more choices to define a given situation.

The parameter d, derived from the linear relationship between numbers of species and logarithms of total individuals generally increased downstream during all seasons (Fig. 16). Margalef (1957) indicated that $\bar{H}$ correlates well with d. In Black Bear Creek, however, no consistent relationship could be discerned. At Station 22 during winter $\bar{H}$ was low and R was high, but d was not significantly different from other seasonal values. $\bar{H}$ and d were relatively similar at Station 125, furthest removed from the source of brine pollution. It would appear that the parameter d as an index of diversity is less precise than other parameters when applied to polluted situations.

The parameter d was used to obtain an index of heterogeneity between stations (Table 10). This index reflects differences in distribution of individuals into species between stations. A low index number is indicative of closely related faunal assemblages while the converse is true for a high index number. Highest index numbers generally occurred between Station 22 and every other station, possibly because nine of the 79 species found at Station 22 were excluded from the lower reaches by oil field brines. The low index number between Stations 100 and 125 indicates close similarities between faunal assemblages.

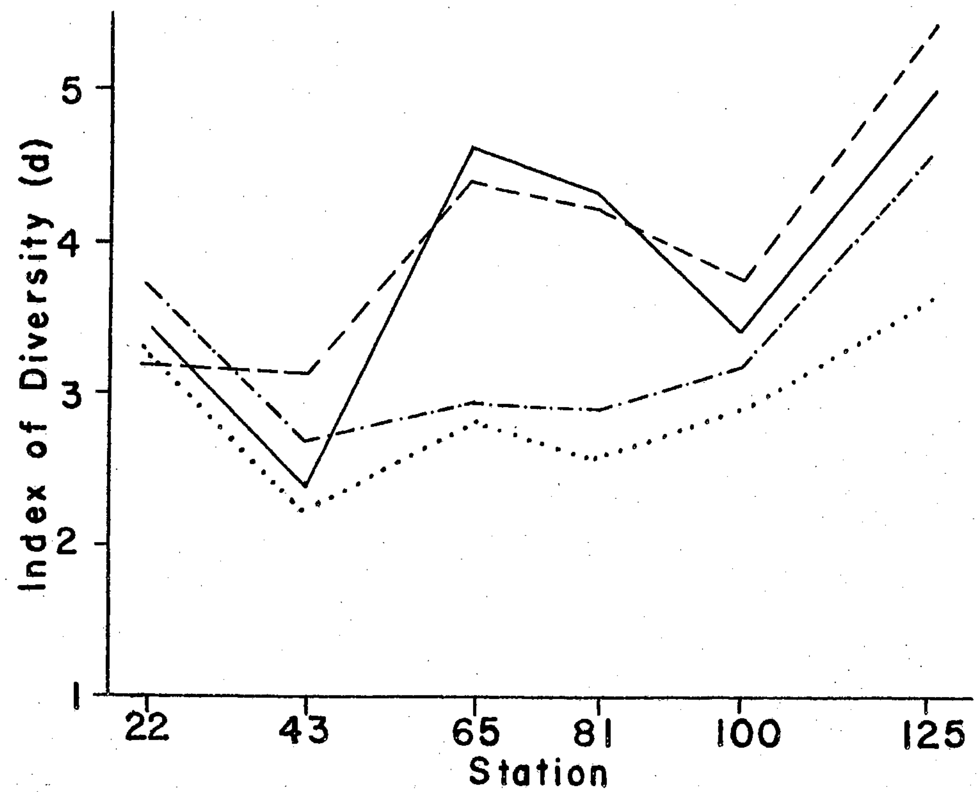

Fig. 16. Seasonal index of diversity (d). See figure 4 for code.

TABLE 10

ANNUAL INDEX OF HETEROGENEITY

Stations	22	43	65	81	100
43	.68				
65	1.26	0.60			
81	1.02	0.94	.65		
100	1.40	0.83	1.04	0.59	
125	1.15	1.26	0.66	0.24	0.09

Since community structure can be defined in terms of precise numerical indices, information theory methods are of value in evaluating stream conditions. An investigator with a limited taxonomic background may use the methods since organisms are recognized at the species level and need not be named. Finally, information theory methods make it possible to compare structure of benthic macroinvertebrate communities in streams with different environmental variables.

CHAPTER V

SUMMARY

1. A study of physico-chemical conditions and community structure of benthic macroinvertebrates in a stream receiving oil field brines was conducted between October 1963 and October 1964. Community structure of benthic macroinvertebrates was quantitatively related to physico-chemical conditions and methods of analysis derived from information theory were applied to community structure.

2. Oil field brines in Black Bear Creek produced high conductivity which varied inversely with turbidity. Turbidity was highest at unpolluted stations and lowest where brines were more highly concentrated. Stream discharge increased downstream resulting in a decrease in conductivity and an increase in turbidity. Conductivity was maximum at all stations during winter when stream discharge was low and relatively constant. Longitudinal variation in bicarbonate alkalinity was associated with brine concentration and was lowest at stations with highest conductivity. Hydrogen ion concentration varied little from station to station but was highest in the downstream reach.

3. Seventy-nine species of benthic macroinvertebrates were collected during this study. Numbers of species varied from 31 at stations below the outfall to 55 at the furthest downstream station. Faunal assemblages in Black Bear Creek were dominated by three families of insects: Tendipedidae, Simulidae and Hydropsychidae. Maximum numbers

of individuals occurred at stations in middle reaches where turbidity was lowest. Large numbers of individuals in middle reaches may be related to increased primary productivity associated with decreased turbidity and increased light penetration. Longitudinal variation in species composition was attributed primarily to effects of oil field brines.

4. An analysis of benthic macroinvertebrate community structure was made by using methods derived from information theory. Maximum diversity per individual ($\overline{H}$) and minimum redundancy (R) generally occurred at the most polluted station and at the lowermost station. Highest diversity per unit area (H) occurred in middle reaches of the stream where large numbers of individuals were distributed among several species. When one or two species dominated the community, $\overline{H}$ was low and R was high.

5. Two other variables were used in analysis of community structure. The parameter d, an index of diversity, increased downstream and reflected a more varied fauna. An index of heterogeneity, derived from the parameter d, showed that greatest differences in faunal assemblages generally existed between the upstream unpolluted station and all downstream polluted stations.

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