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ACID MINE DRAINAGE IN APPALACHIA

MESSAGE

FROM

THE PRESIDENT OF THE UNITED STATES

TRANSMITTING

THE APPALACHIAN REGIONAL COMMISSION'S REPORT, ACID MINE DRAINAGE IN APPALACHIA, PURSUANT TO THE PROVISIONS OF SECTION 302(b) OF THE APPALACHIAN REGIONAL DEVELOPMENT ACT

VOLUME 3

OCTOBER 15, 1969.—Referred with accompanying papers to the Committee on Public Works and ordered to be printed with illustrations

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LETTER OF TRANSMITTAL

TO THE CONGRESS OF THE UNITED STATES:

Pursuant to section 302 (b) of the Appalachian Regional Development Act, I hereby transmit the Appalachian Regional Commission's report, Acid Mine Drainage in Appalachia.

This comprehensive study was carried out by the Commission in cooperation with a special panel of experts convened by the National Research Council of the National Academy of Sciences - National Academy of Engineering. I recommend it for thoughtful consideration by all interested parties.

Richard Nixon

THE WHITE HOUSE
October 15, 1969

LETTER OF SUBMITTAL

THE APPALACHIAN REGIONAL COMMISSION
1666 CONNECTICUT AVENUE
WASHINGTON, D.C. 20235

June 30, 1969

The President
The White House
Washington, D.C.

Dear Mr. President:

As directed under the Appalachian Regional Development Act as amended in 1967, we hereby respectfully submit a report concerning the effects of acid mine drainage pollution in Appalachia together with our recommendations for initiating a more comprehensive approach to control or abate this pollutant in the future.

The Commission acknowledges the advice and assistance in completing this study by the Secretary of the Interior and other appropriate Federal, state, and local agencies.

In addition, the National Research Council of the National Academy of Sciences-National Academy of Engineering convened a special panel of experts on mine drainage pollution to advise and assist us in the conduct of our investigations.

Our study finds that about 10,500 miles of streams in eight states of the Appalachian Region are affected by mine drainage. These streams are polluted by increased amounts of acid, sediment, sulfates, iron, and hardness of which the most significant pollutant is acid.

Of the total stream mileage affected, acid drainage continually pollutes nearly 5,700 miles. Three-fourths of the acid streams occur in the Susquehanna, Allegheny, Monongahela, Potomac, and Delaware River Basins in Pennsylvania, West Virginia, and Maryland.

Eighty percent of the acid mine drainage pollution in Appalachia comes from abandoned mines, thus making public action a necessity in areas where this pollutant is a priority problem because of its adverse effects. Such areas appear to be concentrated in the anthracite coal region of northeastern Pennsylvania and in portions of the bituminous coal fields of southwestern Pennsylvania, northern West Virginia, and western Maryland.

It is estimated that $3.5 million in added annual costs are imposed upon industrial users, municipal water supplies, navigation, and public facilities by acid mine drainage.

However, the general environmental and aesthetic degradation of affected areas, the destruction of aquatic life, and the deterrents to water-based recreation caused by acid mine drainage might well exceed these other more readily measured costs.

A sufficiently wide range of technology is now available to enable municipal and industrial water users to adjust to acid mine drainage pollution in their water supplies.

In addition, during the last several decades, the Federal Government, the Commonwealth of Pennsylvania, and other groups have developed an array of techniques to abate or control this particularly pernicious form of pollution in the Region's streams. However, these pollution abatement techniques are generally expensive, and varied or limited in their ability to provide effective control or abatement of acid mine drainage.

For this reason, continued research is imperative concerning alternative chemical, physical, or biological methods for controlling or treating acid mine drainage pollution and improvements in engineering techniques.

Because of the high cost of controlling or reducing acid mine drainage pollution, any large-scale action program for the control of this pollutant must be based upon carefully considered watershed plans which take into account the costs and benefits of specific technologies and their appropriateness to present and anticipated conditions within a specific basin.

In addition, acid mine drainage is but one of the factors accounting for environmental degradation. Other results of mining affect land and its use by the existence of mine scars, waste piles, related solid wastes, subsidence and underground mine fires. Other water pollutants include sediment, and municipal and industrial wastes. Therefore, a comprehensive approach that simultaneously considers all aspects of environmental improvement is necessary.

The Department of the Interior has estimated that the current nationwide cost for controlling or abating acid mine drainage pollution, usually only one aspect of environmental degradation, to be $6.6 billion.

The costs involved in a comprehensive approach to environmental problems would be much greater, which makes careful planning of a broad-scale action program essential.

Such large costs, which can be borne only over long periods of time, make it essential that careful planning be done to determine priority areas within which it is feasible to initiate comprehensive programs in the near future.

We therefore recommend the following:

1. An action program for controlling and abating acid mine drainage should be part of a more comprehensive pollution control and environmental improvement program for the lands and waters in designated watersheds. Prior to embarking upon a comprehensive action program, therefore, the state or states in question should be required to identify specific watersheds in order of priority in which acid mine drainage, together with other environmental conditions, is a major impediment to future social and economic development and to submit such priorities to the Secretary of the Interior.

2. It is recommended that the Secretary of the Interior administer the mine drainage demonstration program authorized under the Water Quality Improvement Act of 1969, together with other appropriate funds, so that assistance can be provided to plan environmental pollution control programs in priority watersheds where acid mine drainage is the principal problem. It is recommended that the Secretary utilize a portion of these funds for demonstrations of appropriate intergovernmental and other institutional arrangements that could assist in specific watersheds in carrying out a comprehensive control and abatement program. It is recommended that funds provided under the Water Quality Act of 1969 not be concentrated exclusively on technological demonstrations.

3. It is recommended that funds available under the Water Quality Improvement Act of 1969 be supplemented by funds available under the Appalachian Regional Development Act to assist those state or inter-state areas which desire to initiate comprehensive pollution control programs in priority watersheds.

   a. Specifically, the Appalachian Regional Commission, in cooperation with the Secretary of the Interior will utilize funds under Section 302 of the Act to assist states and inter-state areas in planning comprehensive environmental improvement programs in watersheds where acid mine drainage is the principal problem.

   b. Further, Section 214 of the Appalachian Regional Development Act will be utilized where feasible to supplement demonstration grants under the Water Quality Control Act of 1969 for specific facilities involved in a comprehensive watershed pollution control program where acid mine drainage is a high priority problem.

   c. Additionally, it is recommended that authority under Section 205 of the Appalachian Regional Development Act be expanded to permit the Secretary of the Interior to make financial contributions to states for initiating comprehensive environmental improvement programs in priority watersheds where acid mine drainage has been identified as a principal problem.

4. Federal financial participation in an abatement program should occur only when a state has an established program that will assure no further proliferation of acid mine drainage from active mining operations during and after mining. Our review of several case studies indicates that appropriate measures can be taken by mining operators to prevent pollution by acid discharges.

Research is also recommended into the processes of and conditions influencing acid mine drainage formation in order to improve the basis for estimating the impacts on environmental quality from alternative types and locations of mining operations. In addition, research concerning more economical and effective techniques for chemical, physical, or biological control or treatment of acid mine drainage should be continued.

6. It is recommended that the Secretary of the Interior and the Appalachian Regional Commission be directed to report to the President and Congress no later than July 1971 the progress and results of efforts to initiate comprehensive programs and at that time to make further recommendations concerning Federal assistance to support such programs.

In particular, the report should recommend whatever institutional arrangements involving Federal, interstate, state, and local levels of government, as well as the private sector, appear most appropriate for executing these comprehensive environmental programs within specific watersheds.

Very respectfully,

James A. Rhodes

James Rhodes
Governor of Ohio
States' Cochairman
Appalachian Regional Commission

John B. Waters, Jr.

John B. Waters, Jr.
Federal Cochairman
Appalachian Regional Commission

ACID MINE DRAINAGE IN APPALACHIA

Appalachian Regional Commission
1666 Connecticut Avenue
Washington, D. C. 20235

1969

THE ROLE OF THE NATIONAL ACADEMY OF ENGINEERING AND THE NATIONAL ACADEMY OF SCIENCES

In January 1968, the Appalachian Regional Commission sent a letter to Dr. Frederick Seitz, President of the National Academy of Sciences, requesting that the Academy consider assisting the Commission in conducting a study on acid mine drainage pollution. This study was requested by Congress in the 1967 Amendments to the Appalachian Regional Development Act of 1965.

Dr. Seitz referred the request to the Environmental Studies Board which is charged with coordinating all environmental activities of the National Academy of Sciences and National Academy of Engineering. The Environmental studies Board reviewed the request of the Appalachian Regional Commission at its February 14, 1968 meeting. The Board concluded that the Academies should provide assistance to the Commission and asked the NAE-NAS-NRC Committee on Water Quality Management to assume this responsibility. The acceptance of funds in support of advisory services on research, development and engineering programs in the field of mine drainage pollution to the Appalachian Regional Commission was authorized by the Executive Committee of the Council of the National Academy of Engineering on March 4, 1968. In turn, the Committee on Water Quality Management established the Panel on Mine Drainage Pollution Control to provide advice and guidance to the Commission on the following:

1. Design and implementation of the overall study;
2. Evaluation of the work conducted during the study;
3. Analysis of the findings of the specific study efforts and other related information;
4. Review and evaluation of the drafts and final reports of the Commission study staff, submission and comments the Committee and Panel deem appropriate; and
5. Formulation of the pertinent findings and conclusions which would assist the Commission in developing its recommendations.

Because of the magnitude of the task, both the Committee and its Panel were active in providing the services requested by the Commission. In this connection it should be noted that members of the NAE-NAS-NRC study groups serve as individuals, without compensation, contributing their personal knowledge and judgments on scientific and engineering questions of national importance and not as representatives of any organization in which they are employed or with which they may be associated.

The Appalachian Regional Commission is extremely appreciative of the invaluable counsel and guidance given it by the Committee and Panel. The variety and depth of professional experience and talent represented on the Committee and Panel, and their dedication to the task, have been a strong source of guidance to the Commission in carrying out this study. Their many contributions have substantially improved both the study and the report. For these reasons the Commission gratefully acknowledges a deep debt of gratitude to the National Academy of Engineering, the National Academy of Sciences and, in particular, to the members of the Committee and Panel.

APPENDICES

APPENDIX F

THE BIOLOGICAL AND ECOLOGICAL EFFECTS OF ACID MINE DRAINAGE

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SUMMARY

1. Reviewers of the published literature regarding the effects of acids on fish agree that fully developed adult fish can live between pH of 5.0 and 9.0. There are some records that indicate that some species can survive at a pH as low as 4.0. The productivity of aquatic ecosystems is considerably reduced below a pH value of 5.0, thus the yield from a fishery at those pH levels is reduced.

2. The hatching success of salmonid eggs is reduced below pH 4.8.

3. Laboratory experiments indicated that below a pH of 7.0 the spawning of the minnow, Pimephales, is inhibited. Below a pH of 6.0, the minnows failed to spawn. The number of spawnings and the number of eggs produced per spawning by fish held in the pH range of 6.0-7.0 was significantly less than fish in the water of pH 7.6. The percentage of eggs that hatched at a pH of 6.03 was significantly less than eggs that were spawned at higher pH. The data indicated that populations of cyprinids could not be maintained at pH below 6.0.

4. Brook trout are more tolerant than rainbow trout to low pH. Rainbows prefer water above pH 6.0 while Eastern brook can tolerate water between about 5.0 and 6.0.

5. The warmwater species vary in their tolerance to low pH. Field observations indicate a gradation in sensitivity from the least sensitive to the most sensitive fish species, in the following order: (1) brown bullhead (2) pumpkinseed sunfish (3) bluegill sunfish (4) white crappie (5) golden shiner, common shiner, white sucker and golden red horse sucker.

6. Zone I of Slippery Rock Creek (Pennsylvania) having an average pH of 3.7, was devoid of fish. At different stations in Zone III, which had higher pH, the numbers of species increased as the average pH increased. Four species were found at pH 4.3, 7 species at pH 5.2, and 15 species at pH 6.5. At pH 7.6, 20 species were found including pike, largemouth and smallmouth bass.

7. In lakes in Finland with a pH of about 4.2 to 4.4, 4 species of fish were found but only pike were able to reproduce.

8. The lethal and pathological effects of low pH on fish are yet not completely known. The cause of death of fish in low pH is believed to be acidemia, a decrease of blood pH.

9. Acid mine drainage water carries large amounts of dissolved iron salts. The data regarding the toxicity of iron to fish is confusing and contradictory. The percipitated $Fe(OH)_3$ coats the bottom and reduces the production of benthic animals.

10. Although most workers agree that the growth rate of fish is less in acid softwaters, there are several observers who have found that fish can grow well in certain acid waters where food is sufficient.

11. Acid waters can be reclaimed by adding lime. In a study in West Virginia, the pH of a stream was increased from 5.1 to 6.9 and Eastern brook trout reappeared in previously fishless areas.

12. It is expected that the restoration of acid waters to a pH in which fish can live will ultimately result in an improvement of populations of many terrestrial vertebrates that feed to some extent upon aquatic organisms. This increase in birds, reptiles and mammals would enhance the biological interest of an area.

13. The bacterial, fungal and yeast populations of streams acidified with mine drainage are large, varied, and characteristic. Balanced microbiological associations are found in waters with pH down to 2.1.

14. Studies of acid lakes indicate that as the pH increases toward neutrality, so do the variety of plants. The pH must be above 5.0 to permit a variety of plant species to persist.

15. Some algae can tolerate acid waters below 5.0 while others, particularly the blue-green algae, cannot tolerate waters of low pH.

16. Aquatic insect species are limited by pH levels below 4.0. In Roaring Creek, West Virginia, only 3 to 12 taxa are found in waters of median pH 2.8 to 3.8, while 25 or more taxa were found in waters of median pH 4.5 or higher. Aquatic insects of value as fish food can tolerate lower pH than fish. A stream that will support the life of fish will be suitable for a wide variety of fish food organisms.

17. The decomposition of organic matter originating from domestic wastes will be retarded by acid wastes because of the inhibition of bacterial growth by acid waters.

18. It is believed that the addition of warm effluents from industrial establishments or power plants into waters of low pH will make conditions even more intolerable for fish and other useful aquatic organisms.

19. In regard to fishery management procedures, it is believed desirable to bring the pH of water up to levels which Eastern brook trout can tolerate and still exhibit a normal growth rate. This will probably be at or near pH 6.0. The populations should be maintained by a stocking program if the intention is to create and maintain a recreation industry.

20. For the management of non-trout species, the pH should also be brought to pH 6.5. Past experience indicates that areas in which the pH has been returned to satisfactory levels will be repopulated rapidly from stocks in adjacent areas. If the pH allows reproduction, no management procedures such as stocking should be required.

Acknowledgements

The contractor takes full responsibility for this report. There are many, however, who should be acknowledged for their efforts and gracious cooperation which made this report possible. These friends include (and not in order of importance) those who opened their files and allowed the contractor use of good material as yet unpublished. There are those who forwarded copies of academic theses and file documents that were unavailable through regular channels. There are those who helped me interpret data and who criticized sections of my report, and prevented me from making errors. There were those who put me on the trail of knowledgeable people who were able to give me help, and there were those who informed me that their agencies were not working in the field but informed me of agencies that were active. Without the unstinting, gracious, and enthusiastic cooperation of all of these kind people, this report would have been impossible to prepare.

A special mention should be made of Gary L. Pederson of the College of Fisheries who prepared most of the sections on invertebrates, microorganisms and algae. I also wish to mention the very professional secretarial help of Mrs. Mae Kohlwes, my secretary, who unflinchingly transcribed the reams of script (both mine and Pederson's) into the neatly typed material before you.

I know that I have forgotten the names of some people who have helped me. Please forgive me. The names acknowledged in the list are not recorded alphabetically, nor in order of the magnitude of their contribution.

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John Spindler	Anaconda, Montana

Introduction

There are many ecological variables that regulate aquatic populations and it is known any one of these variables can limit a population even if all other factors are suitable. These factors can be physical such as water temperature, water velocity, the bottom substrate, or the amount of light, to select a few. Other factors can be chemical; the lack of certain chemical substances can be limiting, or substances can be in the correct proportions but in too high concentrations. The lack of a substance, dissolved oxygen, or the presence of a substance in large amounts such as a heavy metal, or an imbalance of hydrogen ions, can inhibit or eliminate desirable populations.

The variable that is of concern and will be discussed in the present report is acidity expressed as pH and its effect upon stream ecosystems, with particular emphasis upon fish. In the Appalachian coal country, low pH as well as other undesirable changes in water quality resulting from the coal mining industry, has limited the biological productivity of its waters. This report will deal with the biological effects of acids draining from coal mines, with particular reference to fish and other aquatic life.

Summary of Reviews by Doudoroff and Katz (1950) and EIFAC (1968)

There is a goodly amount of literature which gives an insight upon the pH limits within which fish can exist. The world literature in this regard published prior to 1950 has been critically evaluated by Doudoroff and Katz (1950). The more recent literature, although principally restricted to European fish, has been reviewed by a FAO United Nations Committee under the Chairmanship of J. S. Alabaster (EIFAC working party on water quality criteria for European freshwater fish, 1968, "Water Quality Criteria for European Freshwater Fish," Report on Extreme pH Values and Inland Fisheries. European Inland Fisheries Advisory Commission, Food and Agriculture Organization of the United Nations, EIFAC Tech. Paper (4) 24 p. 1968). Richard Lloyd was largely responsible for the compilation and analyses of the EIFAC report. The findings in these two excellent reviews can be summarized by citing the summaries of Doudoroff and Katz (1950) and that of EIFAC (1968).

Doudoroff and Katz (1950) state: "1. It appears that under otherwise favorable conditions, pH values above 5.0 and ranging upward to 9.0, at least, are not lethal for most fully developed freshwater fishes. Much more extreme pH values, perhaps below 4.0 and well above 10.0, also can be tolerated indefinitely by resistant species. However, regardless of the nature of acid and alkaline wastes responsible, such extreme conditions, associated with industrial pollution, are evidently undesirable and hazardous for fish life in waters which are not naturally so acid or alkaline.

"...4. The common strong mineral acids (that is, H_2SO_4, HCl, and HNO_3), and also phosphoric acid (H_3PO_4) and some moderately weak organic acids (for example, lactic, citric, tartaric, and oxalic acids), apparently can be directly lethal to fully developed fish in most natural fresh waters only when the pH is reduced thereby to about 5.0 or lower (see, however, paragraph 6 below). Differences between the toxicities of chemically equivalent concentrations of the strong acids, which have been variously reported, may be attributed to synergistic action of the acid anions, but are probably of minor importance from a practical standpoint. The resistance of sensitive species to these acids, and especially to the organic acids mentioned above, in relation to pH and other factors (for example, the calcium content of the water) has not yet been adequately investigated, however.

". . .6. The susceptibility of different species of fish to the lethal action of free carbon dioxide varies greatly. Sensitive freshwater species may succumb rapidly at free CO_2 concentrations between 100 and 200 ppm in the presence of much dissolved oxygen. Lower concentrations (100 to 50 ppm, or less) may be lethal after prolonged exposure, or may interfere with the utilization of oxygen at low tensions and with normal development. The amount of carbon dioxide liberated by the reaction of any sufficiently strong acid with dissolved carbonates and bicarbonates in some hard, natural waters can be lethal to sensitive fish. The resulting mortality of fish can occur at a pH value which is not itself demonstrably harmful (for example, above pH 5.0)."

The EIFAC group summarize their findings as follows: "There is no definite pH range within which a fishery is unharmed and outside which it is damaged, but rather there is a gradual deterioration as the pH values are further removed from the normal range. The pH range which is not directly lethal to fish is 5-9; however, the toxicity of several common pollutants is markedly affected by pH changes within this range; and increasing acidity or alkalinity may make these poisons more toxic. Also, an acid discharge may liberate sufficient carbon dioxide from bicarbonate in the water either to be directly toxic, or to cause the pH range 5-6 to become lethal.

Below a pH value of 5.0, fish mortalities may be expected, although some species may become acclimated to values as low as 3.7. However, the productivity of the aquatic ecosystem is considerably reduced below a pH value of 5.0, so that the yield from a fishery would also become less. Some acid waters may contain precipitated ferric hydroxide which may also act as a lethal factor."

General Field Observations on pH Ranges for Fish

The ready availability and widespread use of colorometric indicators and of electrometric pH meters, both of which are readily portable, has allowed the accumulation of good data on the pH of our natural waters. Ellis (1937) in a study of the chemistry of North American fresh waters over a period of five years found that in general the pH of our waters lies between values of 6.7 to 8.6 and that good fish faunas were found in waters with pH of 6.3 to 9.0. Swamp waters, big streams, and swamp lakes often show an acidity between pH 4.5 and pH 6.0, yet have a mixed fish fauna.

Laboratory Studies

There have been many laboratory studies in regard to the pH tolerance of fish. The data obtained in these studies have been listed or summarized by Doudoroff and Katz (1950), EIFAC (1968), and McKee and Wolf (1963).

Most of these laboratory data have been obtained with salmonids, primarily the rainbow trout, which is most readily available of the salmonids. Other species of salmonids used in laboratory studies have been Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). The brook trout (*Salvelinus fontinalis*) a trout that is native to the Appalachians in suitable waters have seldom been used in pertinent studies because of their restricted availability as compared to other salmonids.

Doudoroff and Katz (1950) cite Creaser (1930), Menzies (1927) and Southgate (1948) as observing trout in acid bog waters below pH 4.7.

Lloyd and Jordan (1964) found that the median lethal pH for fingerling rainbow trout, held in water of low carbon dioxide content, is pH 4.5. K. Dahl (1927) found that 80% of yolk sac trout fry (probably rainbow but not specified), held in water acidified with peat, died within 20 days at pH values between 4.7 and 5.4, and 10% died in water at pH 5.1 to 5.7 (pH determined colorimetrically). Fifty percent of yolk sac fry salmon (*Salmo salar*) held in dilutions of peaty water, died in pH 4.5 in 12 days. Yearling brown trout taken from a river with water of pH 5.85 died within 12 to 14 hours at pH 3.3, and survived a pH of 4.1 for 7 days. Lloyd (EIFAC, 1968) suggests that these brown trout may have acclimated to some extent to low pH.

Lloyd (EIFAC, 1968) cites a personal communication of M. Grande who found that the hatching success of salmon eggs in water acidified with sulfuric acid to a pH of 4.59 was 96% compared with only 48% success at a pH of 4.34. Only 50% of eyed brown trout ova hatched in a solution of peat water at a pH of 4.77. Krishna (1963) observed no mortalities in trout eggs and alevins (species not specified) in water acidified with HCl in which pH values fluctuated between 4 and 5, whereas mortalities were observed below a pH value of 4. This experiment was not well controlled for neither the free CO_2 content nor the length of the experiment were reported.

Carpenter (1927) found that the minnow *Phoxinus phoxinus* survived for 28 hours in a soft water acidified with HNO_3 to a pH of 5.0, while they survived for three days at a pH of 5.2. Jones (1939) using a similar water acidified with HCl found that stickleback (*Gasterosteus aculeatus*) survived for about 5½ days at a pH 4.8 and lived for as long as the control fish (10 days) at a pH of 5.0. Volodin (1960) tested the tolerances of various developmental stages of the ling (*Lota lota*) to various low pH levels and found that successful development could only take place within a narrow pH range. The most sensitive stage was that of embryonic segmentation at which a pH value of 6.0 was the critical lower level. During subsequent development, the critical level was found to be 5.0. Dyk and Lucky (1956) found that the period of motility of carp sperm was reduced in water acidified with peat to a pH of 6.5; Elster and Mann (1950) demonstrated a decreased motility of carp sperm at pH 4.5, and lower pH values were lethal.

F. Trama (1954) held bluegills with no mortality for 96 hours at pH 3.92 to 4.15 in a flowing water system. Using water acidified with HCl in two experiments at pH 3.80, 70% and 80% of the fish, respectively, survived for 96 hours. The minimum pH value for survival is about 3.90.

Mount's studies - reproduction and early development

The most complete and best controlled study regarding effects of low pH on the reproduction and early development of fish is one that is currently being carried on by Dr. Donald I. Mount of the Federal Water Pollution Control Administration, Duluth, Minnesota. (Mount made data available to the compiler.)

The fish used was the fathead minnow Pimphales promelas which according to Trautman (1957) is tolerant to extremes in pH. The tests were conducted in continuously renewed water. The control pH level was 7.6, and the test solutions were maintained at pH 6.82, 6.03, 5.40 and 4.7. One-day-old Pimphales fry were started at the control pH in all aquaria. In the experimental aquaria the pH was reduced to the final experimental level by the following procedure. After one week acclimation at any pH, the pH was dropped to the next level (for the fish that were to be maintained at lower levels) until the full array of experimental pH levels was established.

The fish were held for eleven months in the test waters. The fish became sexually mature and the first eggs were laid at the end of three months. The fish in the control pH, 7.6, were the first to spawn and from January 6, 1967 to March 26, 1967 only fish in the control spawned. In March, the photoperiod was reduced and then increased to simulate natural lighting conditions and to stimulate spawning. Fish in the control pH 7.6 and pH 6.82 and 6.03 subsequently were observed to spawn. Below pH 6.03 no egg deposition was recorded. The fish laid their eggs on the underside of tiles and each day the eggs that had been deposited were counted and removed. Fifty eggs from each spawning - except in cases where there were less than fifty eggs - were placedin a small basket and incubated in the same aquarium for seven days at which time the number of eggs that had produced viable fry was determined. The percentage of eggs that hatched was calculated. The fry that had hatched were held in water of the same pH at which they had hatched, for 30-60 days, at which time they had developed adult characteristics.

Observations

No egg production was observed in tanks containing water of pH 4.7 and 5.4. Eggs were collected 57 times in the control, pH 7.6. At pH 6.82, eggs were collected 26 times while at pH 6.03 eggs were collected 13 times. There were approximately nine spawnings per female in the control, three spawnings per female at pH 6.8 and about 1.35 spawnings per female at pH 6.03. One may safely state that reduction of the pH below that of the control reduced the frequency of spawning.

Average number of eggs per spawning

The average number of eggs collected after each spawning in the control was 138 eggs. At the pH 6.82 the average number of eggs produced was 74 eggs and at pH 6.03 the average number of eggs produced was 83.4. (Note: The difference in egg production at pH 6.82 (74 eggs) and pH 6.03 (83.4) is not regarded as significant.)

These data do not indicate that the number of eggs spawned per female was less in the more acid waters because we have no way of telling if more than one female deposited eggs in each tile collector. There is no doubt, however, that the total egg production in the two tests conducted at pH 6.82 and pH 6.03 was greatly reduced This can be emphasized by observing that in the control pH 7.6, a total of 7849 eggs were produced, at pH 6.82, 1934 eggs were produced, and at pH 6.03, only 1085 eggs were produced.

Hatchability of the eggs

Eggs that were deposited were removed from the tiles and placed in small baskets and replaced in the test aquaria. At the end of seven days the number of fry that were hatched was determined.

In 31 hatching experiments at the control pH, a 74.5% average hatch was obtained. In 18 experiments at pH 6.8, an average hatch of 82.4% was obtained. Eggs for hatching experiments were obtainable only seven times at pH 6.03 and the percentage that hatched was 43%.

These data suggest that adequate fish populations of this species might be maintained at the pH of 6.8 but there is room for serious doubt that the population structure could be maintained by the increments of eggs and fry produced at pH 6.03.

Field Observations

Menzies (1927) has observed native populations of brown trout in water of pH 4.5 and Campbell (1961) has observed them in water of pH 4.9. Creaser (1930) reported that Eastern brook trout were found in waters with a pH as low as 4.1. (Creaser's conclusions seem to be based on an analysis of other peoples data and upon some of his observations made in a previous study. The validity of Creaser's conclusion is deemed doubtful.) M. Grande in a personal communication to R. Lloyd (EIFAC, 1968) observed that salmonids were absent in waters where the pH value fell below the range 4.6 to 4.8 - "This may be the results of the susceptibility of the eggs and fry to these values." The presence of the fish reported by Creaser, in water of low pH, may be due to the fact that these fish might spawn in tributaries where the pH is high enough for the survival of the eggs and larvae.

Lennon (Personal Communication, 1959) stated that it is generally accepted that "brooks are more tolerant of low pH than rainbows." Lennon observed that in some streams in New Hampshire, with pH near neutrality, rainbow trout outnumbered brook trout. The subsequent establishment of beaver ponds, with a concurrent decrease in pH, however, strongly favored the brook trout over the rainbow. In time, the pH in some of the beaver ponds decreased to about 4.0 and the brook trout soon disappeared.

Lennon also observed that pH seems to be a limiting factor to rainbow trout in the Smokies (Great Smoky Mountains National Park). He said (personal communication), "A mainstream may contain a good rainbow population upstream to a junction of two nearly equal forks. Fork A may contain rainbows and some brook trout to the upper limit of fishable water. Fork B, on the other hand, may be completely barren or contain only brook trout. The only significant difference in the two streams may be the fact that Fork A has a pH over 6.00 and Fork B has a pH below 5.5."

Lennon also reported that "In every case in the Smokies where rainbow have failed to move into barren waters or to invade brook trout waters, the only consistent factor has been low pH. We are trying, therefore, to manage low pH waters solely for brook trout."

Lennon (1967) cites King (1943) as listing a pH range of 4.7 to 6.9 for brook trout waters in the park. Lennon commented that "we measured a range of 5.2 to 6.0 in the head water streams and 6.8 to neutrality in the main streams."

Arnold Benson (1967) studied the distribution of fish in relation to pH in a 29-mile stretch of the Monongehela River south of the West Virginia-Pennsylvania state line. The result of his population studies "demonstrate a fairly consistent distributional pattern corresponding to the degree of environmental acidity. A gradation of species from the most tolerant to the most sensitive was established in the following order (1) brown bullhead (2) pumpkinseed sunfish and bluegill sunfish (3) white crappie (4) golden shiner, common shiner, white sucker and golden red horse sucker."

Unfortunately, the pH at which these species persisted was not given in the cited report.

Benson also reported that the 48 hour TLm (TLm - median tolerance limit - pH at which 50% of test fish survived for 48 hours) for river pumpkinseed sunfish is within the pH range of 3.25 to 3.36.

Benson (1968), in a second report, found that pumpkinseed sunfish are more tolerant to acid water than bluegills. He mixed acid mine water with river water and found that all bluegills died within 24 hours at a pH 3.50-3.58. Pumpkinseed survived in comparable pH ranges for periods as long as 72 hours. These laboratory studies confirmed field tests in the Monongehela, i.e., that the marginal pH for the survival of sunfish ranged from pH 3.1 to 3.6. Golden shiners tested in live boxes in the river failed to survive at a pH of 3.6.

A comprehensive biological study of Slippery Rock Creek, Pa. was made by Shellgren et al. (1967). The distribution of aquatic life was correlated with chemical parameters including pH. Shellgren divided the stream and its watersheds into three major areas. In Zone I, the pH varied on an average from 3.0 to 5.0. The station furthest downstream in Zone I had an average pH of 3.7. The iron content at the different stations were from 3.2 to 6.4 ppm. Zone I was biologically unproductive and no fish were taken or observed in Zone I.

Zone II included all portions of the Slippery Rock Creek watershed from the junction of the South Branch to the junction of Wolf Creek (Stations T-7 through 10). The average pH in the mainstream in this area averaged from 4.3 to 6.5. The iron content in the mainstream averaged from 0.24 to 0.50 ppm. Obviously, chemical conditions in the stream had improved. At station #8 (Keisler's), average pH 4.3, 77 fish belonging to 4 species were found; at station 9 (average pH 5.2), 213 fish belonging to 7 species were found, and at station 10 (average pH 6.5), 187 individuals belonging to 15 species were found. At stations 8 and 9, where the variety of fish was limited, 90% of the fish were the creek chub, Semotilus, and the sunfish Lepomis. At station 10, the fish population consisted of unusually large adults which suggested to Shellgren a "migration upstream from the mouth of Wolf Creek rather than a resident population" which would have been composed of all size classes.

Zone III included all of the Slippery Rock watershed from Wolf Creek to Wurtemberg. The average pH of the main stream stations ranged from 7.6 to Moore's Corners (Station 12) to 7.8 at station 16. The fish populations at all stations in Zone III consisted of many individuals and a variety of species. At station 12 (average pH 7.6), 853 individuals of 20 species including the pike Esox, largemouth and smallmouth bass were present. At the other stations, the numbers of species ranged from 11 to 17. The change in species composition at the various stations in Zone III was due probably to the types of habitat rather than to water chemistry.

Shellgren's observations indicate that somewhere between 5.2 to 6.5, conditions improve enough to allow a variety of species to survive. It is probable that a pH range close to 6.0 is necessary for an adequate fish population.

R. W. Warner of the Federal Water Pollution Control Administration, Cincinnati, Ohio (1968) made a thorough study of the periphyton and the benthic animals of Roaring Creek, West Virginia, a stream receiving acid mine drainage. Warner stated that the U.S. Fish and Wildlife Service had determined that fish populations inhabited those reaches of the stream where the median pH was 4.9 and higher. Fish found in the Roaring Creek Basin were brook trout (Salvelinus fontinalis), mottled sculpin (Cottus bairdi), blacknose dace (Rhinichthys atratulus) and the creek chub, Semotilus atromaculatus. The eggs of rainbow trout (Salmo gairdneri) which were planted, failed to develop (Burner, 1967). Warner (personal communication, 1968) confirmed that brook trout were found at a station in which the median pH was 5.1, while at an adjacent station on the same stream where the median pH was 4.9 they were absent.

Although it is recognized by most workers that biological conditions in acid lakes do not parallel those observed in acid streams, observations made in acid lakes are of interest. Vallin (1953) reports that in a lake in Northern Sweden (Lake Blamisus) the water has a pH of 2.8 to 3.1 and a Fe content of 6 to 7 ppm; the flora and fauna are lacking in variety and number and fish are absent. The water from this lake flows into Lake Sladen which has a pH of 3.7 to 3.8 and the iron content is reduced 0.3 to 1.2 ppm. The flora and fauna are more abundant and varied in Lake Sladen and perch, pike, and two species of cyprinids were present. In the spring, the pH falls to 3.5 to 3.7 and mortalities of a cyprinid, the roach, are observed. Ryhanen (1960) made a study of Lake Sysjarvi in Finland and reported that the pH in this lake varied from 3.5 (at the outlet of an acid stream) to 4.6 with the major part of the lake with a pH value of 4.2 to 4.4. Bream, perch, roach and pike were present but only pike were able to reproduce in the zones where the pH values were between 4.2 and 4.4. No small fish of the other species were present and it is believed that the bream, perch, and roach were derived from fish that spawned in the more alkaline streams feeding the lake. The growth of pike, however, was observed to be slow. These findings are supported by the experimental work of Donald Mount with Pimephales which was discussed above. Mount observed that spawning was unsuccessful or inhibited in waters of low acidity, below pH 6, a pH at which adults could live and grow.

The effects of low pH on fish

The pathological effects of low pH on fish has been investigated by several workers. Namba and Karlya (1967) examined the blood lactic acid of carp held under different pH conditions. The blood lactic acid level was not affected at pH 4.2. A rise to about 50 mg % lactic acid was observed in carp which were killed at pH 3, or had been suffocated in water of pH 4.2.

The toxicity of hydrogen-ions to goldfish has been ascribed by Ellis (1937) to be due to the precipitation of mucus on the gill epithelium resulting in death by suffocation or by precipitation of proteins within the epithelial cells (Westfall, 1945). Kuhn and Koecke (1956) subjected goldfish to solutions of HCl and H_2SO_4 in distilled water and found that exposure to pH 4.0 for one hour led to a complete destruction of the gill epithelium. This observation is difficult to correlate with the observations of others who have held fish for long periods of time in water of lower pH and failed to observe any abnormal mucus production or tissue damage.

Schaeperclaus (1933) stated that a persistent pH of 4.8 causes a milky turbidity of the skin of carp, the destruction of the gills with a succeeding fungus infection, and the formation of a brown epidermis. Schaeperclaus (1933) observes that in the presence of iron, pH values of 5.5 are dangerous for carp. Fe precipitates in large flakes upon the gills which are alkaline. Sometimes, however, these pathological manifestations are not observed. Schaeperclaus also noted that trout are most sensitive to low pH, and that pike and tench are less sensitive than carp.

Schaeperclaus also observed that even at temperatures as low as 4-5°C a secondary attack of constipation is observed in fish in acid water. He also observed that trout eggs die and become fungused after being held in water at a pH of 4.8. A high content of iron in the water aggravates the condition.

Lloyd and Jordan (1964) found no evidence of gill tissue damage or precipitated mucus in rainbow trout after they had died after 7½ hours exposure to a solution of pH 3.4. They also observed that rainbow trout which had been immobilized after 24 hours in a solution of pH 3.8, recovered on transfer to water of pH 8.2. The pH value of the venous blood of rainbows killed by water of pH 3.15 was 0.2 pH units lower than that of control fish that had been held with water with little free CO_2. The venous pH of the blood of fish was 0.55 units lower in fish dying in water of pH 4.50 and containing 50 ppm free CO_2. These authors believed that in rainbow trout, the cause of death at low pH is acidemia.

Acidity and Fe

The toxicity of acid mine waste is complicated by the fact that these waters often contain large amounts of dissolved ferric sulfate which a pH's greater than 3.0 hydrolyze to form ferric hydroxide (Dahl, J. 1963). This process is accelerated by the presence of the sulfur bacteria, Thiobacillus sp. (Fjeringstad, 1958, and Dahl, 1963). Vallin (1953) observed that roach which have been killed in acid waters with a high Fe content have brown deposits, presumably an iron compound, on their gills.

Haupt (1932) found that one-year-old carp died in a water of pH 4.3 to 4.4 containing between 1.2 to 10.5 ppm Fe. Larsen and Olsen (1948) observed fish kills in a trout hatchery when the pH value was 6.2 to 7.0 and the water contained from 1.5 to 20 ppm Fe. The cause of death was attributed to the precipitation of $Fe(OH)_3$ on the gills, since the pH value of the water was much higher than the generally accepted lethal pH values. Jones (1939) found that the toxicity of solutions of ferric chloride in soft water could be accounted for by the low pH value and believed that the ferric salts had a very low toxicity. Lloyd (1968) remarks that only 1 ppm Fe was required to give the threshold pH value in the dilution water used by Jones, and it is probably that this concentration of iron was too low to have a toxic action if precipitated. If fish are killed by ferric hydroxides in suspension, the concentrations which appear to be lethal are lower than those found for inert suspended material (EIFAC, 1964). The presence of the precipitate on the gills of dead fish does not necessarily indicate that this was the cause of death.

One of the more interesting observations in regard to iron toxicity is that of LaRoze (1950,1955) who studied the mortality of trout in a hatchery with a water supply which was contaminated with drainage from a mine which contained some pyrite deposits. LaRoze decided that the mortality was caused by the iron in the water (about 1 ppm) but the deaths could not be attributed to precipitated iron hydroxide nor to Fe ions. LaRoze believed that basic iron salts, probably in a semi-colloidal state, were injurious and these salts were capable of penetrating and damaging the gill tissues. He stated that the effects of the iron could be demonstrated by microchemical examination of the gill tissues of fish which had been exposed to Fe containing water. Treatment of the excised gills with 10% HCl and then with potassium ferricyanide solution produced a diffuse blue coloration which was detectable microscopically. LaRoze asserted that the iron within the gill tissues could thus be readily distinguished from harmless superficial deposits.

Doudoroff and Katz (1953) observe that the data regarding the toxicity of dissolved iron to fish is confusing and contradictory and believe that a properly planned and conducted experimental program is required to answer the numerous divergences of opinion regarding the toxicity of Fe and Fe compounds to fish. Lloyd (1968, EIFAC) states "In the cases where toxicity is not complicated by the presence of ferric salts, the data on fish kills are in reasonable agreement with the results of laboratory experiments."

Effects on the growth of fish

Most workers agree that the growth rate of fish is usually less in acid and in soft waters than in the more alkaline waters, but the available data do not throw much light on the reasons for this. Campbell (1961) found there was no correlation between pH and the growth rate of brown trout in nine lakes with pH values ranging from 4.9 to 8.4. He suggested that the slow growth rates of fish observed in some acid lakes, influent to which were adequate spawning streams, was due to a population density too great for the food supply. Both Campbell (1961) and Pentelow (1944) found that the growth rate of brown trout artificially stocked in low pH waters to give a low population density was equal to that of fish in alkaline lakes.

Lloyd (1968) mentions a communication by E. Twomey (Dept. of Agriculture and Fisheries of Eire) that the growth rate of brown trout in Irish rivers and lakes was generally higher in alkaline waters, but the best growth rate observed was in a lake with a pH of 5.4.

Briuchanova (1937) found that crucian carp and common carp appeared to feed normally over the tolerated pH range, but that the maximum growth was achieved at a pH value of 5.5 for crucian carp and 6.0 to 6.2 for common carp. Lloyd (1968) mentions a personal communication by H. Mann who observed in northern Germany the optimum pH range for carp growth was 6.8 to 7.5, but below 6.0 the growth rate is reduced. This reduction is associated with a reduced food supply. Parsons (1952) on the other hand, reports "amazing growth" of blue-gill sunfish in a pool with a pH of 4.5.

Frost (1939) concluded that some factor other than available food was responsible for the lower growth rates of trout in the acid headwaters of the river Liffey compared with that of the more alkaline downstream sections.

The effects of treatment procedures upon the biology of streams

There is little in the available literature detailing the changes in ecology of acid waters after treatment although studies currently are being made in West Virginia and Pennsylvania. It has been common practice in the European carp pond fisheries to correct for acid in ponds with soft waters by liming. Schaeperclaus (1933) states (in translation), "The value of liming can hardly be expressed in figures. In very many ponds, in fact, commercial operation is only possible after liming." On p. 166 of Schaeperclaus (1933) is an illustration of a water wheel used to distribute lime into streams flowing into carp ponds. Frost and Brown (1967) fertilized a very soft water pond (about 3 ppm $CaCO_3$). The alkalinity was 19.5 ppm $CaCO_3$ four months after the first treatment. It was observed that after the first two applications of lime the fauna of the bottom mud was increased significantly. The pea clam, Pisidium was ten times as abundant and the increase of the alga Nitella, afforded more habitat for aquatic insects which resulted in increased abundance of the mayfly, Cloeon.

Zurbuch (1963 reported his observations in a stream which had been limed with a water wheel mechanism. The stream treated was Otter Creek in the Monongehela National Forest of West Virginia. Previous to treatment, no fish had been observed in Otter Creek and its tributaries downstream to Moore's Run. A native brook trout population (Salvelinus fontinalis) exists in the main stream above the Condon Run tributary. Bottom fauna were nearly non-existent in the fishless sections.

Zurbuch described his waterwheel drum in considerable detail and also reported on the various sizes and types of limestone used in his preliminary experiments. Zurbuch discussed the use of blast furnace slag for the neutralization of acids. Slag not only has considerable calcium carbonate but significant amounts of trace elements particularly magnesium, manganese, boron, zinc, copper, molybdenum and cobalt.

It was observed during the operation of the liming station that the stream was milky immediately below the treatment station but most of this turbidity disappeared within the first 400 feet; 850 feet below the station the turbidity was only slightly greater than that of the stream above the liming station. There was a visible deposit of finely ground limestone in the streambed.

Zurbuch found that the liming increased the pH of the stream water almost two pH units, or from about 5.1 to about 6.9. The increased pH persisted to the conjunction of Otter Creek and Dry Fork. It was further observed in the summer of 1961 that the stream did not abruptly return to the former acid conditions when treatment was stopped. In one instance, Condon Run after two weeks of treatment remained above pH 6.0 for two days after liming had been stopped. The pH of Condon Run was 5.1 above the treatment plant.

After a period of prolonged treatment, two brook trout were observed in waters not formerly inhabited with fish. In a live box experiment, brook trout were placed in the stream above and below the treatment section. The pH of the untreated water at the time of the test was 4.9 and within 3 days all fish were dead in the untreated section. Only one of 10 fish placed in the stream below the treatment station died within the two-week test period. No studies of benthos were made by Zurbuch.

This study on the liming of Otter Creek has been continued as a Dingell-Johnson project by the West Virginia Department of Game and Fish (D.J. Report F-12-R-5 Limestone Drum Productivity Study, West Virginia Department of Game and Fish). The results of the fish studies are presented in condensed form in a report entitled "F-12-R-5 Job No: 2." The data indicate that the brook trout population continued to increase below Station 4, which is immediately below the treatment plant. The estimated number of fish at Station 4 was 268 individuals in the spring of 1967 which is far greater than the 119 collected in the spring of 1966; the 51 collected in the spring of 1965; and the one fish observed in 1964. The increase in the population was ascribed primarily to increased production and survival of young-of-the-year fish. The numbers of older fish increased slightly over 1966. The small fish observed were the result of natural reproduction.

Young-of-the-year trout were collected for the first time at Station 5 which is 1.1 miles below the treatment plant and fish were observed at Station 6 which is 3.5 miles below the treatment site.

At Station 8, 7.3 miles below the treatment plant, the pH had decreased to a median of 5.3 (range 4.7-5.7) and no fish were observed.

At Station 3, immediately above the treatment plant the median pH was 5.3 (range 4.9-5.7) and only 6 trout were observed. At Station 4, the median pH was 6.9 with a range 5.3-7.3.

Unfortunately, no chemical sampling was conducted at Stations 5, 6, and 7. It would have been interesting to know if the slow spread of the fish population was due to a reluctance of the trout - especially the young-of-the-year - to leave their "home" areas, or whether there was a gradual decrease of pH downstream that inhibited the fish from moving into the more acid waters.

If the fish were relatively non-migratory and would not be inhibited in their growth by the decreased pH that presumably occurs at the stations downstream from the drum, then a program of planting small fry would be of value to restoring the fish population rapidly, and would restore the stream as a recreational resource. It must be noted, however, that the study apparently was designed to determine how rapidly a native trout population would repopulate a barren area rather than to study the survival of a planted group of fish (Raymond Menendez, Personal Communication, 1968).

In addition, the West Virginia workers concurrently studied the larger benthic organisms in Otter Creek. They made two collections per year each year since 1964 of the bottom insects, the crayfish, and salamanders. Although in the progress report available to us, the insects were not identified by their taxonomic group, it is presumed that they were the larger a quatic insect larvae commonly utilized by fish as food. The benthic collections were quantitative. Each station consisted of 30 square feet of bottom except during some dry summers when part of some stations were no longer covered with water. The data obtained are condensed into Table 1. The data regarding the benthos are not too instructive for evaluating the biological changes caused by the acid. The data in the West Virginia report suggests that the benthic species composition (number of species) is about the same (per collection) at all stations. The number of species varied from a mean of 20.2 species at Station 1, an unpolluted control, to 14.2 mean species at the control station just above the drum (median pH 5.3) and 14.3 mean species at Station 9, where the pH was 4.7-5.3 (estimated). The mean number of species at the stations just downstream from the limestone treatment drums were: Station 4B, 16.5 species, pH 6.9; Station 5, 17.1 species; Station 6, 17.6 species; Station 7, 17 species. We cannot say that the decrease in the number of species at Station 9 is a result of the acidity there (presumably pH 5.3 or less) because it is known that many physical factors in a stream besides water quality dictate the composition of a fauna. (Moore and Clarkson, 1967)

Menendez (R. Menendez, Personal Communication) points out that the smaller crop of insects, 113 individuals per collection, immediately below the liming station, is due probably to (1) a silting effect caused by residue of fine limestone particles and (2) cropping by the trout population which is relatively large at this station. Menendez also stated that the complete data obtained in this study would be published as a Master's Thesis within a year or so.

Table 1. The variation in number and the mean number of insect species, crayfish, and salamanders and the mean number of insects taken at the various stations on Otter Creek with variation in pH and the median pH. (West Virginia Dept. of Fish & Game, D.J. Report F-12-R-5)

	Total # Species Mean # per collection	Mean # of Insects per collection	# of Crayfish Mean # per collection	# of Salamanders Mean # per collection
Unpolluted	17-25		0-7	0-7
Station 1	20.2	199.8	3.5	3.5
Unpolluted	16-23		0.9	0-7
Station 2	18.1	325.6	4.0	2.2
Station 3	13-21		1-27	0-7
pH 4.9-5.7	15.6	286.7	11.1	2.5
Median 5.3				
Station 4	12-19		0-4	0-1
pH 5.3-7.3	16.5	113.4	2	.2
Median 6.9				
Station 5	13-20		0-14	0.10
	17.1	315	8.5	2.4
Station 6	15-21		1-17	0-8
	17.6	264	9.3	2.5
Station 7	13-20		0-17	0.12
	17.0	454	6.1	3.3
Station 8	14-18		0-15	0.13
	16.1	285	6.9	2.8
Station 9	12-19		0-10	0-2
pH 4.7-5.3	14.3	223	4.3	0.8

Another example of the return of an acid polluted stream to biological productivity by liming treatment is that of the Clark Fork River in Montana (R. W. Boland, Personal Communication, 1968) and Foote (1962). The Clark Fork River has been grossly polluted by the acid wastes from the refinery at Anaconda, Montana, since about 1902. These wastes also contain copper and iron salts. About 1960, the refinery began a waste treatment procedure which essentially consisted of adding a lime slurry to their acid water and precipitating the resulting $FE(OH)_3$ floc. The final pH of the treated effluent is about 8.3. About 7 million gallons of water are treated every day and between 100-200 tons of lime are used daily in the treatment. Because of this treatment over 60 miles of the Clark's Fork was returned to fish production. The species of trout that predominate are brown trout and fishing below the effluent was regarded as good to excellent (John Spindler, Personal Communication, 1968).

In July, 1967, workers at the Anaconda refinery went on strike and remained on strike throughout the summer. The strikers included those workers responsible for the waste treatment operations. Discharge of the untreated acid waste waters entering the Clark Fork resulted in massive fish kills. Complete data on the effects of the fish kill are not available but there is no doubt that severe biological damage has occurred. The Montana Department of Fish and Game has collected large amounts of data on the Clark Fork River prior to treatment, during treatment, and have documented the biological effects of the lack of treatment during the strike. These data, when analyzed and made available, should be instructive.

The effects of acid water upon terrestrial vertebrates

There is no authoritative data in the available literature regarding the effects of water pollution, let alone acid mine drainage, upon terrestrial vertebrates, although there is no doubt that many naturalists or observant residents have observed the decline or extinction of certain species of birds, animals, amphibians or reptiles in the areas in which waters have become polluted. Perhaps one reason for this lack of published information is the inability of biologists to separate the effects of water quality declines from the many other man-made ecological changes that are usually synchronous in the same areas.

No way has yet been developed to correlate declines in water quality with changes in populations of aquatic birds, mammals, amphibians or reptiles. On the other hand, it probably would be difficult to measure the beneficial effects on these same vertebrates of an effective program designed to control acid mine drainage and to restore a stream to productivity. Yet, there is every good reason to believe that the restoration of acid polluted streams to biological productivity will be accompanied by an influx of birds and animals that rely upon the streams for a substantial amount of their food and habitat.

Although many of these animals in themselves are of limited direct economic value, their presence in or adjacent to a stream adds much of value, their presence in or adjacent to a stream adds much of value to the stream for the recreationist. The restoration of the terrestrial and amphibian fauna is a tangible (although probably small) added benefit that would accrue as a result of a water quality improvement program.

Birds

Many species of birds that are listed in the bird fauna of the Appalachian region are known to eat fish and other aquatic animals. Pough (1951) lists many of these birds and gives an account of their food habits.

The common loon is reported to have a diet of fish, crayfish, shellfish and amphibians. The red-necked grebe is reported to eat fish. The horned grebe feeds upon fish, crayfish and tadpoles, and a large part of the freshwater diet of the double-crested cormorant is made up of perch, bullheads, crappie, sticklebacks and salamanders. The spotted sandpiper eats freshwater crustacea and small fish. The kingfisher, a common resident upon almost all bodies of water with fish populations, feeds primarily upon desirable fish species (Blair, *et al.*, 1957).

The American merganser is listed by Kortright (1962) as primarily a fish eater but also feeds upon molluscs, crustaceans and fish eggs. They are known to feed upon trout. The hooded merganser and the red-breasted merganser are also fish and crustacea feeders.

Obviously, the re-establishment of a suitable aquatic fauna will result in a response by the bird species which utilize these aquatic organisms as their food supply. Although a fisheries manager would not be pleased to observe an influx of winged predators, bird watchers and non-predatory recreationists would be happy to observe them. It would be hazardous to compute and compare the expenditures of a fisherman as compared to a bird fancier but each group will contribute usefully to the economy of a recreation-oriented community.

Reptiles

Although reptiles are not always regarded with popular favor, they also contribute to the biological interest and variety of an area. The highlight of a fishing trip may be the sight of a large watersnake slowly swallowing a sucker - an act which this writer once observed with great interest.

Ditmars (1937) reported that the common water snake, *Natrix sipodon*, pursues and eats slow-moving fish, frogs and toads. The ribbon snake (*Thamnophis sauritus*) also feeds on small fishes, tadpoles and frogs.

Turtles are also fish eaters.. Carr (1952) examined the stomach contents of 51 Blanding's turtles, Emys blandingii, and found their food consisted of (by volume): crustaceans 56.6%, game fish 1.6%, molluscs 2.6%, forage fish 2.70%. Carr reported that the common map turtle fed almost exclusively upon aquatic snails and crayfish. In Michigan, these turtles will feed upon fish although over 50% of their diet was crayfish.

Forty-seven and four tenths percent of the stomach content of the Eastern spiny soft-shelled turtle (Amyda ferox spinifera) in Michigan was crayfish (Carr, 1952). Carr also reported that the spineless soft-shelled turtle (Amyda mutica) ate fish.

The common snapping turtle (Chelydra serpentina serpentina) was reported by Carr to eat game and pan fishes. In Michigan, 34.2% of the stomach contents of these reptiles were fish. Carr (1952) observed that the stomach content of 71 specimens of the common musk turtle (Sterothenus odoratus) consisted of by percent volume: game and pan fish 6.2%, crayfish 6.2%, snails and clams 23.2%.

The presence of reptiles as well as birds contributes to the interest of an area. The restoration of the water quality of a stream to the level in which fish will prosper will help provide food for the reptiles that may repopulate the reclaimed area.

Mammals

Many of the smaller mammals of the Appalachian regions utilize aquatic species as part of their food and it is reasonable to expect that populations could be affected adversely by changes in water quality that reduce the biota of the waters.

The opossum (Didelphis marsupialis virginiana) is reported by Cockrum (1962) to eat many species of freshwater molluscs. The raccoon (Procyon lotor) is reported by Cockrum to feed extensively on crayfish. A study in N. E. Colorado indicated that 9.8% of their diet consisted of crayfish. Cowan and Guiguet (1965) report that raccoons feed on almost any aquatic animals that they can capture including fish, crayfish, snails and frogs. Hamilton (1939) reported a study in Michigan in which 500 raccoon feces were examined. Crayfish remains were found in 59% of these. In addition, some mollusc remains were found.

Cockrum (1962) found that frogs made up 25% of the diet of mink (Mustela vison), fish were 20%, and crayfish were 9.3%. Cowan and Guiguet (1965) stated that mink feed upon fish, amphibians and reptiles. Cockrum (1962) reported that the bobcat feeds upon fish when available. Cowan and Guiguet (1965) reported that muskrats eat freshwater mussels.

Hall and Kelson (1959) reported that the diet of river otters (Lutra canadensis lataxina) consisted of fish, crayfish, frogs, turtles, and aquatic invertebrates. Hamilton (1939) examined the stomach of river otters and found suckers and quantities of crayfish.

Obviously, some of the most interesting mammals of the United States are dependent upon the rivers for an important part of their food supply. Any significant increase in water pollution will reduce the population of these interesting and valuable species and conversely the return to production of the acid polluted rivers and streams will be to the advantage of not only the aquatic biota but to their vertebrate predators.

A very useful report in regard to mine drainage and wildlife which became available when the drafting of this report was almost complete was that of Boccardy and Spaulding (1968). This report confirms the difficulty in differentiating and evaluating the relative effects upon wildlife of the alteration of water quality by acid drainage, and the ecological disturbances of the land surface that accompany the strip mining. For example, they estimate that an additional one to four acres of land may be destructively disturbed for each acre of coal recovered by this type of mining. This statement would suggest that the wildlife species of the greatest economic and recreational importance, the deer, would be greatly affected. Yet Cromer (1967) reported that the West Virginia 1966 deer harvest of 21,249 animals was "the second highest in the history of the state." Another brief report from West Virginia entitled, "1967, Official Deer Harvest, Game Kill for 1967" give a kill of 18,318 animals for 1967. Although Cromer does not make any conclusions or statements to this effect, the tenor of his report indicates a feeling that the deer populations are at satisfactory levels and he gave no indication that any ecological factor outside of "total acreages of forested and non-forested land" is of prime importance in regulating the West Virginia deer herd. (The writer of this report dwells upon the West Virginia deer data because Boccardy and Spaulding report that West Virginia has the greatest percentage of its land (1.24%) and presumably of its waters affected by mining activities.) Yet there are some conservationists who might take the position that if the damage to theland and waters resulting from the strip mining were not present, the deer kill might be significantly larger. This stand is partially supported by Boccardy and Spaulding's observation that "wildlife unwilling to drink acid water is usually absent near badly polluted areas." Although data and observations are lacking in the literature, the only reasonable conclusion that can be derived is that many terrestrial vertebrates are affected deleteriously by acid mine drainage, and it also seems reasonable that restoration of water quality will benefit vertebrates other than fish.

The effects of pH on aquatic invertebrates and plants

Microorganisms

Lackey (1938) did not take special bacterial samples during his study of acid waters, but some water samples taken for other purposes showed some motile forms. Bacterial masses of the "zoogleal" type were also found. Fungi were surprisingly rare. Galionella was abundant in a few samples only.

During a study of Ohio acid streams (pH 2.0-4.0) Joseph (1953) isolated 40 species of bacteria. Of these 40 species, 14 were of the genus Bacillus, 20 were of the genera Micrococcus or Sarcina, 2 were of the genera Eschericia or Aerobacter and the remaining species were of the genera Thiobacillus, Crenothrix, and Microsporium.

It is now generally accepted that bacteria are directly associated with acid formation. Thus, it is not surprising that iron and sulfur-oxidizing bacteria have been found to be indigenous to acid mine water. Thiobacillus thiooxidans, Thiobacillus ferroxidans and Ferrobacillus ferroxidans have been the most commonly reported (Temple and Koehler, 1954; Weaver and Nash, 1968).

Renwick (1968) in a study of the microflora of an acid (pH 2.3-4.1) strip-mine lake found organisms of the genera Thiobacillus and Ferrobacillus to be abundant. Heterotrophic bacteria and fungi were also fairly abundant, especially Penicillium sps.

Tuttle et al. (1968) compared the bacteria in an acid stream with those in a non-acid stream. They found that the non-acid stream contained low numbers of acid-tolerant heterotrophic microorganisms. These acid-tolerant aerobes survived and increased as the stream became more acid until the pH approached 3.0. A stream which was acid did not have a similar microflora. Iron and sulfur-oxidizing autotrophic bacteria (Thiobacillus-Ferrobacillus group) were common, with the sulfur-oxidizing bacteria predominating over the iron-oxidizers. Fungi were not as well represented as Joseph (1953) anticipated in his study of Ohio acid waters. Organisms of the genera Aspergillus, Helminthosporium, Penicillium, Trichoderma, Cladosporium, Alternaria, and Tricholhecium were isolated. In general, he found a positive correlation between bacterial and fungal counts per ml and the pH of the water.

By means of several isolating techniques, Cooke (1966) found large numbers of fungus colonies in acid mine streams. Many of these same species have also been found in streams draining areas that were not polluted by acids, and in streams receiving sewage treatment plant effluent. Active species may be beneficial in removing organic pollutants from the water and at the same time may also stabilize iron. Apparently, true fungi are not involved in the transformations leading to "acid mine drainage" or to the reduction of acidity in the habitats in which they grow.

Weaver and Nash (1968), in comparing the number of fungal species found in 2 different branches of Beaver Creek, one branch which received acid drainage (pH below 4) and one which did not receive acid drainage (pH 6.3-6.7), found that fungi were more numerous in the acid branch. A total of 41 genera were found; 17 were isolated from both branches; 20 from the acid branch, and 4 only from the non-acid branch.

Yeasts have been commonly reported from acid streams. Cooke et al. (1960) isolated 3 genera of yeasts - Candida, Rhodotorula, and Trichosporon - from acid streams. Rogers and Wilson (1966) isolated several species of Rhodotorula and Trichosporon cutaneum from acid waters of the Monongahela River. Ehrlich (1963) also isolated yeasts of the above genera from acid drainage of a copper mine. Weaver and Nash (1968) found that Rhodotorula appeared consistently in an acid branch of a creek but was not found in a nearby non-acid branch of the creek.

Ehrlich (1963) found evidence of a balanced microbiological system in mine drainage water of a pH of 2.5. Bacteria of the Ferrobacillus-Thiobacillus group were present along with yeasts resembling Rhodotorula and Trichospora. A protozoan resembling Eutrepia was observed feeding on the yeasts and bacteria. This microbial population suggests the existence of a balanced ecosystem in which carbon fixation is dependent on chemosynthetic not photosynthetic autotrophy.

Aquatic Plants

Lackey (1938) stated that the common cattail (Typha latifolia) was observed growing in streams receiving acid mine drainage, and lakes, but no other spermatophytes were observed.

Heaton (1952) found that as the pH of the acid-mine water decreased, the number of species of plants increased. During Crawford's study in 1942, the pH of Lake "A" varied from 2.8-3.0, while in 1952 it varied from 3.0-3.8. This increase in pH, evidently, was not enough to allow aquatic plants to become established as none were found during either study.

In Lake "B" the pH had risen from 2.4-3.8 to 5.5-7.1 (Heaton, 1952). During the earlier study only Eleocharis palustris, Typha latifolia and Carex sp. were reported. In a span of 10 years, 7 new additional species were able to invade Lake "B" with its increased pH. Pondweed (Potamogeton diversifolius) was the most common aquatic plant and during summer and early fall this plant covered most of the lake bottom.

During the 10-year period, between studies, Lake "C's" pH rose from a mean of 5.3 to 7.0. During the earlier study the only aquatics found here were the same 3 species found in Lake "B". Virtually the same plant species invaded Lake "C" as had invaded Lake "B", but were less abundant due to the higher turbidity of Lake "C".

Harrison (1965) in his study of South African acid-mine streams (pH 4.3 and lower) also found Typha latifolia to be abundant. Sedges and rushes were also commonly found.

In Illinois, Bell (1956) found that only emergent species occurred in waters with pH values below 6.4. These were both species of cattail, Typha latifolia (down to pH 3.0) and T. augustifolia (pH down to 4.5).

Ehrle (1960) found that aquatic vegetation was very rare in 36 Pennsylvania streams with a pH range of 3.05-4.6. The only truly aquatic species found was *Eleocharis acicularis*. It appeared to thrive forming large, bright green, vegetative mats.

Moore and Clarkson (1967) studied areas on 3 acid rivers in West Virginia in an effort to determine factors that regulate the distribution of aquatic plants. The most abundant vascular aquatic plant was *E. acicularis*. Other common plants were *Sagittaria graminea*, *S. latifolia*, *Potamogeton epiphydrus*, *P. nodosus*, *Sparganium americanium*, and *Myriophyllum heterophyllus*. Sedges, rushes and cattails occurred rarely.

Using a statistical analysis, Moore and Clarkson established that the most important factor for vascular aquatic plant establishment and growth in the areas studied was the substrate. Once the plants became established, four factors become important: fluctuation of the water level; total acidity; pH; and phosphate content. Thus, in the areas studied, acid mine water did not appear to play the significant role in controlling the absence, abundance, or distribution of the vascular aquatic plants.

It is apparent from the above literature review that there are still important questions regarding the effect of acid waters on aquatic plants. Heaton's work would indicate that pH was the determining factor for the distribution of aquatic plants in lakes; while Moore and Clarkson's study indicated that substrate was the most important factor in rivers. This lack of agreement can only be resolved by careful additional study.

Stream algae and microinvertebrates - field observations

Lackey (1938, 1939) found that algae were common in some acid streams (pH 4.8 or lower) while almost lacking in others. His samples indicated a tolerance for acid conditions by *Actinophrys sol*, *Chlamydomonas* sp., *Chromulina* sp., *Euglena mutabilis*, *Oxytricha* sp., *Urotricha farcta*, *Navicula* sp., *Ulothrix zonata* and a rotifer, presumably *Distyla*. Of these organisms, *Euglena mutabilis*, *Oxytricha*, *Navicula* and the rotifer were the most abundant. Worthy of note is the lack of blue-green algae, none were found below a pH of 3.7 and only one (*Oscillatoria* sp.) below 7.0.

Harrison (1958, 1965) in a study of South African acid streams (pH below 5) found that filamentous algal types and diatoms dominated the algal flora. The common filamentous types most often found were *Sphaerocystis* sp., *Oedogonium* sp., *Mougeotia* sp., and *Tribonema* sp. Several species of diatoms occurred commonly including: *Eunotia exigura*, *Frustulia magaliesmontana*, *F. rhomboides* var. *saxonia*, *Pinnularia acoricola*, *P. subcapitata*, *Achnanthes microcephala*, and *A. minutissima*.

Steinback (1966) observed that the number of algal species found at a certain station correlated directly with pH values and distance from the source of pollution. The closer to the source of the mine drainage and the lower the pH, the fewer the algal species. Steinback consistently found *Eunotia* spp., *Navicula* spp., *Chlamydomonas* spp., and *Euglena mutabilis* in waters of pH 3.0 and lower. *Ulothrix* sp., *Microspora* sp. and *Mongeotia* sp. were found in water with pH values of 3.5. The cyanophyta (blue-green algae) were typically absent in streams receiving acid mine drainage. Lackey had also made this observation. At one station (pH of 5.5) Steinback did find an abundant growth of Oscillatoria.

Warner (1968) compared severely polluted (median pH 2.8-3.8) reaches of Roaring Creek, West Virginia, with less severely polluted (median pH 4.5 or higher) reaches. He found that the severely polluted reaches supported 10-19 taxa of periphytic algae while the less severely polluted sections contained 33 or more species of algae. Warner's data indicate that pH 4.5 is the breaking point between a well balanced population complex of algal species and the restricted population of a stream markedly affected by acid wastes.

Among the 64 species of periphyton collected from Roaring Creek, 10 species (Ulothrix tenerrima, Microthamnion strictissumum, Microspora pachyderma, Closterium acerosum, Chlamydomonas sp., Eunotia exigua, Pinnularia termitina, Frustulia rhomboides, Surirella ovata and Euglena mutabilis) were particularly tolerant of severe acid mine pollution. However, only U. tenerrima, P. termitina, E. exigua and E. mutabilis were present in large numbers in the more acid reaches.

Shellgren et al. (1967) in their study of Slippery Rock Creek, Pa. found Hormidium to be the only common alga in the most severely polluted reaches (pH range 3.0-3.7). Microspora and diatoms occurred rarely. In less severely polluted reaches (pH range 3.6-5.2) Hormidium and Ulothrix were abundant with Oscillatoria and diatoms common while Scenedesmus, Mougeotia staurastrum, and Euglena occurred rarely.

The diatoms of acid mine streams in West Virginia and Pennsylvania were investigated by Joseph (1953). Navicula viridis was the most common; however, a total of 8 genera and 18 species of the class Bacillarieae were found. The multitude of diatoms in every acid stream examined by Joseph led him to suggest that these organisms may be used as an index of acidity. Diatoms were the most abundant form of life found in the streams examined by Joseph. Six of the 18 species were of the genus Navicula. Unfortunately, Joseph does not give the pH ranges for his samples and this mars the usefulness of his data.

Stream benthos - field observations

Kinney (1964) estimated that 5,890 miles of stream in the United States have a potential for fish and wildlife habitat if their pollution by acid could be reduced. Unfortunately, very few good field studies have been done regarding the effects of acid mine drainage on benthos of streams.

Harrison and co-workers, 1958, 1960, 1962, 1965, in their studies of South African streams polluted by acid mine drainage found that streams with a constant pH below 5 have an impoverished fauna. This fauna is characterized by a small number of species of animals, but sometimes the populations of these species are large. The typical fauna consisted mainly of chironomids, some caddisflies and mites.

A species diversity index was used by Steinback (1966) in his study of acid streams in Ohio. He found a good correlation between pH and the species diversity index. For example, at his station farthest from the source of mine drainage and with the highest average pH 4.57, the average species diversity index was 1.06, while at the station nearest the pollutional source the average pH was 2.67 and the average species diversity index was 0.21. At pH levels of 3.0-3.5 the chironomid *Tendipes* sp. was common as was the Neuropteran *Sialis*. Caddisflies and Odonata began to appear in waters of pH 3.5 or higher.

In an investigation of the biota inhabiting Roaring Creek, West Virginia, Warner (1968) found that highly acidic stream reaches (median pH 2.8-3.8) were inhabited by 3 to 12 taxa of benthic invertebrates while less acidic reaches (median pH 4.5 or higher) supported diverse communities of 25 or more taxa. There was an extremely sharp break in the number of invertebrate taxa at 4.5. Below pH 4.5 the benthic biota was limited. Above pH 4.5 a varied benthic fauna existed. One concludes from Warner's data that good mixed benthic species complexes could exist above pH 4.5.

A number of bottom-dwelling animals, including the alderfly, (*Sialis* sp.), bloodworm midges (*Chironomus* sp.), and other species of chironomidae and dytiscid beetles tolerated very low pHs. These forms were often very abundant; up to 16,675 *Chironomus plumosus* per square meter were collected from an area with a median pH of 2.8. During the summer months, the caddisfly, *Ptilostomis* sp. could be found at all stations containing leaf litter regardless of the pH of the stream.

Blackflies, crayfish, mayflies and stoneflies were repeatedly collected at stations with a median pH of 4.5 or higher, but never were collected in reaches with median pH values below 4.5, thus showing their extreme sensitivity to acid pollution.

Shellgren *et al.* (1967) studied the benthos in Slippery Rock Creek watershed which receives large amounts of acid mine drainage. In the upper portion of Slippery Rock Creek (Zone 1) where most of the acid mine drainage occurs, the average pH of 5 stations ranges from 3.0 to 3.7. No aquatic insects could be found at any of the stations. In Zone II, downstream from Zone I, recovery began to take place. The average pH of 3 stations rises from 4.3 to 5.2 to 6.5 units, while the number of benthos increased from 0 to 1 to 10, respectively. Zone III, the lowermost portion of Slippery Rock Creek sampled in this study, shows pHs on the alkaline side and the presence of normal fauna; that is, an abundance of organisms with a diversity of species.

Carter (1964) presents data to support his use of mayflies as indicators of clean, unpolluted water. Little Hurricane Fork which was of good quality supported 129 mayflies/20 ft^2 of stream bottom, whereas Hughes Fork which was polluted with acid supported only 15 mayflies/20 ft^2 of stream bottom. In the Beaver Creek Basin, Kentucky, bottom samples were collected in the Hilton Branch and the Cane Branch. Unpolluted Hilton Branch supported a rich variety of organisms, whereas only Diptera were found in the acid mine drainage polluted Cane Branch. Sampling was continued over a period of 3 summers and in that time, Hilton Branch was observed to support 8 orders of Insecta, Oligochaeta, Crustacea, and Amphibia. In contrast, Cane Branch's fauna was represented by 4 orders of insects only, of which no more than two orders were collected during any one collection. The orders collected in Cane Branch besides Diptera were: Megaloptera, Odonata and Hemiptera.

Benthos - Environmental requirements

Roback (1965) recorded the number of times a Trichopteran (caddisfly) genus occurred at a certain pH range for 100 stations on 25 rivers. Unfortunately, none of the rivers had a pH between 3.0 and 6.0, so the only data of interest is the occurrence of 6 species at a pH of less than 3.0. These 6 species are as follows: Phylocentropus, Cheumatopsyche, Macronemum, Athripsodes, Oecetis, and Brachycentrus.

Curry (1965) reported the environmental pH ranges of many midges. The species Prodiamesa olivacea, Corynoneura sp., and Lauterborniella gracilenta have been reported from waters with a pH of 4.4. Polypedilum illinoense, Tantytarsus jucundus, Cryptochironomus fulvus and Tendipes attenuatus have been found inhabiting waters of pH 4.0.

Benthos - Laboratory studies

Stickney (1922) found that nymphs of the dragonfly Libellula pulchella could live at a pH of 1 for at least 12½ hours.

Bell and Nebeker (1968) completed a laboratory study on the short-term tolerance of 10 species of aquatic insects to low pH. Table 2 is a summary of their results. They observed that some species, both caddisflies (Brachycentrus and Hydopsyche) were tolerant to low pH. The median tolerance limit of all species was below pH 4.65 and 8 of the 10 species had a median tolerance limit pH 3.68 or less.

It is obvious from the above observations that many of the aquatic insect larvae that are utilized by the carnivorous species such as trout or bass are more tolerant to low pH than fish. Therefore, in a rehabilitation program of a quite acid stream in which the pH is increased by small increments, one would observe first a reinvasion by aquatic insects. When the pH is finally increased to a value high enough for fish, an adequate food supply would be reestablished if sufficient time had elapsed for insects to colonize.

Table 2. The tolerance of aquatic insect larvae to low pH. Included are the toxicity threshold (the pH below which mortalities occurred within 96 hrs) the 96 hr TLm (the pH at which 50% of the organisms died within 96 hrs) and the 0% survival level (the pH at which none of the organisms survived for 96 hrs).

(Modified from Table 2 and Figure 3 of Bell and Nebeker (1968))

Species	Mean 96 hr TLm pH	Toxicity threshold pH	0% Survival pH
Brachycentrus americanus (caddisfly)	1.5	3.5	-
Hydropsyche betteni (caddisfly)	3.15	4.4	2.0
Taeniopteryx maura (stonefly)	3.25	4.9	2.0
Boyeria vinosa (dragon fly)	3.25	4.5	2.0
Acroneuria lycorias (stonefly)	3.32	4.6	2.0
Stenonema rubrum (mayfly)	3.32	4.6	2.0
Ophiogomphus rupinsulensis (dragonfly)	3.5	4.8	2.0
Isogenus frontalis (stonefly)	3.68	5.1	2.0
Pteronarcys dorsata (stonefly)	4.25	5.4	3.0
Ephemerella subvaria (mayfly)	4.65	5.8	4.0

Lackey (1938,1939) was one of the first to study plankton in waters affected by mine drainage. Most of his samples were from streams and since he makes no effort to separate his results according to lake or streams, his results were discussed under the stream section.

The most complete studies of plankton in acid polluted waters are those of Crawford (1942) and Heaton (1951). It is instructive to compare Heaton's (1951) data with the data collected by Crawford (1942) in the same lakes.

Lake A In the 10-year interval between the 2 studies, Lake A's pH increased from an average 2.9 to an average 3.3. This small rise in pH is the reason for this lake changing the least of any studied. The rotifer, Brachionus urceolaris, was the dominant plankter during both investigations. The diatoms Synedra, Frustulia, and Fragillaria were present during both investigations. Navicula was not found during the second investigation while the numbers of Chlamydomonas was less.

Lake B In the earlier study (Crawford, 1942) this lake was highly acid, average pH 3.8, while during the latter study (Heaton, 1951) this lake approached neutrality (average pH 6.6).

The greatest changes in plankton species occurred in this lake. The crustaceans Ceriodaphnia, Cyclops, Bosmina, Daphnia and Diaptomus invaded the lake after the earlier study. Eleven new species of rotifers were present during the second study as compared to the original investigation when Brachionus was the only rotifer. The most important invading rotifers were: Keratella, Notholca, Polyarthra and Pedalion.

The number of genera of Chlorophyceae increased from 6 to 17. Seven new genera of desmids were found in the lake. Chlamydomonas decreased in abundance in the lake. The flagellates Dinobryon, Mallomonas, Synura, Peridinium, and Ceratium were important invaders in this lake.

Lake C In Lake C, the average pH increased from 5.3 to 7.0. The increase in the number of plankton species during this period was only slightly less than in Lake B. During Crawford's study Cyclops was the only crustacean present, while during Heaton's study the following additional species were taken: Ceriodaphnia, Daphnia, Diaptomus, and Bosmina. The number of rotifers increased from 3 genera, Brachionus, Keratella, and Polyarthra to 11 genera. The most numerous rotifers during the latter study were Notholca, Pedalion and Asplanchnopus.

There was a marked increase in the number of species of algae found in the lake. Formerly Synedra and Navicula reached peaks of 2,000-3,000/l while neither was more abundant than 30/l during the latter study. Chlorophyceae increased from 8 to 12 genera with 3 species disappearing from the lake. Pediastrum which had reached a peak of 300/1 during the original investigation was absent during the second study. The same 5 flagellates that invaded Lake B also appeared in Lake C.

In 1962-1963, the 3 lakes previously studied by Heaton and Crawford, plus an additional highly acid lake were investigated (Campbell et al. 1964).

Lake A_1, the lake not previously studied, had a pH of 2.0-2.9 and contained only 1 planktonic species, Euglena. Lake A_3 (Lake A in the earlier studies) had a pH of 2.7 in 1940, 3.3 in 1950, and 4.0 in 1962-1963. The number of species of plankton showed little increase from 11 to 12 to 13 during the 3 studies. The most common planktonic organisms were the desmid Closterium sp. and the rotifer Brachionus urceolaris. The pH of Lake B has increased over the years as follows: 1940-3.8; 1950-6.6; and 1963-7.2. The number of species of plankton went from 15 to 51 to 35. The more numerous species in 1962-1963 included: Dinobryon divergens, Synura uvella, Ceratium hirundinella, Aphanocapsa sp., Keratella cochlearis, Bosmina longirostris, Diaphanosoma leuchtenbergianum, Ceriodaphnia lacustris, and Diaptomus pollidus.

Stockinger and Hays (1960) studied the plankton of 3 Kansas strip-mine ponds, two of which are of interest because of their acidity. Lake 1 was strongly acid with a pH ranging from 3.2-3.6. The plankton population was restricted, with rotifers and microcrustaceans comprising 90% of the volume. Diatoms were collected throughout the study, but were usually unimportant quantitatively. Desmids and the flagellate Ceratium sp. were observed only twice. Microcrustacean genera occurring most frequently were: Cyclops, Daphnia, Diaptomus, and Scapholeberis. Rotifers occurred in all collections with Keratella the most numerous.

The pH of Lake 2 varied from 6.2-7.2. In general, it was slightly acid throughout most of the year. In contrast to the benthos (see discussion on lake benthos) this lake supported a slightly larger plankton population than Lake 1. Here again, rotifers and microcrustaceans comprised over 90% of the volume. Diatoms occurred commonly, but were unimportant quantitatively. Cyclops were numerous throughout the study, while Daphnia were present throughout the study but comprised only a small percentage of the total. Ceriodaphnia, Bosmina, Diaptomus, and Scapholeberis were present only sporadically and in small quantities. Rotifers were present in all collections, with Keratella the most common genus.

Riley (1960) surveyed the plankton of 6 Ohio strip-mine lakes of varying age and pH. Only 2 are of interest in this discussion. One of the lakes was a year old and the water was pH 4.0. The only plankton occurring was an abundant population of Navicula. The other lake of interest was 22 years old and had a pH of 5.5. Only 5 algal species were found and these occurred rarely: the 5 species included the green algae Cosmarium, Pleurotaenium, Zygogonium, a desmid and the diatom Navicula.

Steinback (1966) found two organisms previously unreported for waters polluted by acid mine drainage. Peridinium inconspecuum and Closterium acutum were the dominant plankters in a reservoir that received acid mine drainage (pH range of 3.5-4.5).

Lake Benthos - Field Observations

Lackey (1938, 1939) in a study of acid streams in West Virginia and acid lakes (pH 1.8-3.9) in Indiana found only 12 species of macroscopic invertebrate fauna. The only crustacea observed were a few *Gammarus* in 2 streams whose pH values were 2.2 and 3.2. The most abundant insect species was the midge *Coretha* (*Chaoborus*). In many of the Indiana pit lakes, *Chironomous* larvae were plentiful. Also reported occurring infrequently were a few mosquito, mayfly, and caddisfly larvae.

The type and consistency of the substratum is usually conceded to be of primary importance in determining the types of invertebrate fauna present. However, lakes and streams that receive acid mine drainage possess such a degree of acidity that it is probably a more important limiting factor than the substratum (Crawford, 1942). Recent work by Shellgren (1968) supports this hypothesis. He found that in an acid stream that had been neutralized, colonization of iron-covered rocks occurred rapidly. Within 1½ months the mayflies *Ameletus* and *Epeorus*, the caddisflies *Hydropsyche* and *Philopotamus*, and the cranefly *Pedicia* had colonized iron-covered rocks. Damselflies, stoneflies (*Perlestra*) and Coleopterans had not colonized the iron-covered rocks but were found on adjacent rocks that were not coated with iron deposits.

To date, the most comprehensive study on the fauna of acid strip-mine lakes is that of Heaton (1951). He studied the same 4 lakes that Crawford studied in 1942, thus allowing him to follow changes in faunal succession in the lakes as the pH changed.

Lake A In the 10-year interval between the 2 studies, Lake A's pH increased from average 2.9 to average 3.3. This small increase caused little change in the benthos since the acidity was still very high. Chironomids and Ceratopogonidae were present during both investigations while two new species, the dobsonfly *Sialis* and the beetle larva *Ilybius*, were observed by Heaton. The weight of benthic fauna showed an increase from 0.975 g/m^2 (8.7 lb/A) to an average of 26.81 g/m^2 (239 lb/A). However, this change may be partially or wholly the result of variations in populations rather than an ecological succession in the lake.

Lake B During the earlier study (Crawford, 1942) this lake was found to be highly acid, average pH 3.8, while during Heaton's study this lake approached neutrality (average pH 6.6). Not surprisingly, the greatest increase in the number of new species occurring in any one lake since the earlier study was found in Lake B.

During 1940-1941, only 3 resistant insects (chironomids, ceratopogonids, and dragonflies) were present in Lake B. In 1949-1950, 13 additional faunal species were taken. Among the more important invading organisms were the mayflies *Hexagenia*, and *Caenis*, the midge *Chaoborus*, and molluscs. The total weight of the benthos showed an increase from 1.793 g/m^2 (16 lb/A) to an average of 5.74 g/m^2 (51.19 lb/A).

Lake C In Lake C; the average pH increased from 5.3 to 7.0. In the earlier study, this lake was observed to support some Chaoborus, Caenis, and Oligochaeta in addition to the chironomids, ceratopogonids and dragonflies. Ten years later, 12 new species were taken in the lake reflecting the decrease in acidity. Formerly chironomids comprised the major portion of the benthos, but in the later study Chaoborus and Caenis showed tremendous increases in number. Hexagenia and the mollusc, Musculium, also comprised an important part of the bottom fauna. The weight of benthos increased from an average of 0.456 g/m^2 (4.07 lb/A) to an average of 10.68 g/m^2 (95.28 lb/A).

The fourth lake - Lake D - had an average pH of 7.2 during the first study and changed little over the 10 year period. Due to its neutral or alkaline nature, it is not of interest in this discussion.

Heaton suggests that while acidity is undoubtedly the dominant controlling factor for production, he also recognizes that the amount of leaves and other organic matter falling into the lakes is very important. This organic material serves as the basis for much of the production of benthos and probably plankton.

Confirmatory evidence for this proposition is reported by Harp and Campbell (1967) in a study of the distribution of Tendipes plumosus in 19 strip-mine lakes including the ones studied by Crawford and Heaton. T. plumosus was the sole tendipedid occurring in the most acid lakes. Its development was not limited by the degree of acidity except in the most acid lake (pH 2.3) where its emergence from the pupal stage was unsuccessful. Distribution of this species did not appear to be limited by the mineral acidity of the lakes, but by the absence of leaf detritus.

In 1962-1964 the 3 lakes previously studied by Heaton and Crawford were once again investigated (Campbell et al. 1964). An additional highly acid lake was also studied.

Lake A_1, the lake not previously studied, had a pH of 2.0-2.9. Only 2 forms of aquatic insects were collected, Corixidae and Ceratopogonidae. Lake A_3, (Lake A in the earlier studies) which had a pH of 2.7 in 1940, 3.3 in 1950, and 4.0 during the last study, also had an increase in the number of groups of bottom organisms from 2 to 4 to 12 in the respective years. The most abundant benthos were larval stages of Tendipedidae. The pH of Lake B has increased over the years as follows: 1940-3.8; 1950-6.6; and 1963-7.2. The subsequent increase in groups of bottom fauna was 3 to 14 to 17. The bottom fauna was dominated by Chaoborus, Caenis and Tendipedidae.

Stockinger and Hays (1960) studied 2 acid strip-mine lakes in Kansas. Lake 1 was strongly acid with a pH varying from 3.2 to 3.6. Insects comprised the bulk of the benthic fauna as to number and volume. Gyrinus was the only common coleopteran larva. Other coleopteran larvae found were: Laccophilus, Haliplus and Berosus. Diptera larvae were common with Tendipes the most abundant. Other dipteran found besides Tendipes were: Palpomyia, Bezzia, Pentaneura, Calopsectra and Chaoborus. Odonata were found in large numbers and comprised an important segment of the benthic fauna. Odonata genera most frequently found were: Trapezostigma, Aeschna, Libellula, Ischnura and Enallagma. Sialis was the only representative of the order Megaloptera.

Lake 2's pH ranged from 6.2 to 7.4 with the average slightly acidic. Surprisingly, this lake was poorer than #1 in benthos production. Oligochaetes were more numerous than in Lake No. 3. Tendipes and Chaoborus were the most numerous dipterans. Mayflies were present, in small quantities, in the fall. Odonata were not numerous.

Two possible explanations were advanced for Lake 1 having a larger benthic population than Lake 2. The increase in benthic volume is attributed to the Tendipes and Odonata which are pioneer acid-tolerant groups. These acid-tolerant groups apparently live successfully in an environment which is devoid of many other groups of organisms and hence competition is lacking. The second possible explanation is that Lake 2 had a fish population which may have reduced the standing crop of the bottom organisms.

Table 3. A generalized summary of some effects of pH on freshwater fish.

Range	Effects
3.0-3.5	Unlikely that fish can live more than a few hours. Blood lactic acid level of fish abnormal. Blood pH of rainbow trout reduced.
3.5-4.0	Lethal to salmonids. Some evidence that roach, tench, perch, pike can survive possibly after a period of acclimation to slightly higher pH levels. Bluegills may not survive while pumpkinseed sunfish can. Destruction of gill epithelium at pH 4.0.
4.0-4.5	Perch, bream, roach and pike can become acclimated to this pH and survive but only pike can reproduce. Decreased motility of carp sperm. The fish populations are limited in number and only a few species can survive. Blood lactic acid level of fish normal.
4.5-5.0	Likely to be lethal to eggs and fry of salmonids and a salmonid population could not reproduce. Harmful but not necessarily lethal to carp. Adult brown trout can survive in peat waters.
5.0-5.5	Not harmful to any species unless CO_2 is high (over 20 ppm) or water contains iron salts (debatable). May be lethal to eggs and larvae of sensitive fish species. *Pimephales* failed to spawn.
5.5-6.0	Eastern brook trout in Appalachian waters survive at over pH 5.5. Small populations of relatively few species can be found. Growth rate of carp reduced.
6.0-6.5	Unlikely to be harmful to fish unless CO_2 is over 100 ppm. Some eggs at all stages of development can survive. Time of spawning of *Pimephales* inhibited. Frequency of spawning of *Pimephales* greatly reduced and number of eggs produced is very small. Percentage of *Pimephales* eggs hatching greatly reduced. Rainbow trout can survive in Appalachians. Good populations with a varied species composition can exist.
6.5-7.0	Harmless to fish unless heavy metals or cyanides which are more lethal at low pH are present. Time of spawning of *Pimephales* retarded. Frequency of spawning of *Pimephales* significantly reduced and number of eggs significantly reduced.
7.0	Good mixed populations including bass and pike can be found.

Table 4. A generalized summary of effects of low pH on invertebrates and plants.

Range		Effects
below 3.5		All flora and fauna generally severely restricted in number of species; however, numbers of a particular species may be great.
	1.	Microorganisms - Bacteria Thiobacillus-Ferrobacillus group common; yeasts and fungi common component of microflora.
	2.	Algae - Often only 2-3 algal species found, Euglena mutabilis and Eunotia exigura often found in large numbers; microcrustaceans may be common.
	3.	Benthos - Tendipedids, chironomids, **ceratopogonids**, and Sialis are common.
	4.	Plants - Generally not found at this low of pH, cattails occur occasionally.
3.5-4.0	1.	Microorganisms - All flora and fauna generally severely restricted in the number of species; however, numbers of a particular species may be great.
	2.	Algae - Diatoms may be dominant algae, flora little changed.
	3.	Benthos - Caddisflies and Odonata begin to appear; Tendipedids and Chironomids still dominant.
	4.	Plants - Cattail (Typha latifolia) only common plant.
4.0-4.5	1.	Microorganisms - Biological species complex similar to previous range but yeasts beginning to be replaced by bacteria.
	2.	Algae - Little change.
	3.	Benthos - Similar to previous range.
	4.	Plants - Cattails still common; Eleocharis may be abundant.
4.5-5.0	1.	Microorganisms - Biological species complex similar to previous range.
	2.	Algae - Number of different taxa increases greatly.
	3.	Benthos - Diverse fauna of benthic organisms begins to appear; number of different species makes large increase. Blackflies, mayflies and stoneflies begin to appear in numbers.
	4.	Plants - Little change

Table 4 - continued

Range	Effects
5.0-6.0	1. Microorganisms - Yeasts and Thiobacillus-Ferrobacillus bacterial group become less important; bacterial species diversity increases.
	2. Algae - Diatoms may no longer be dominant; flagellates and green algae are common; many new species occur; Oscillatoria may be found, only blue-green alga commonly occurring at pH lower than 7.0.
	3. Benthos - Little change.
	4. Plants - Most aquatic plants will grow at this range if substrate, water velocity and fluctuation are satisfactory.
6.0-7.0	1. Microorganisms - Fungi are being replaced by additional bacterial species; microflora quite "normal." *
	2. Algae - Essentially "normal." *
	3. Benthos - Relatively "normal"*; molluscs begin to occur commonly.
	4. Plants - "Normal" * flora.

*"Normal" is used here to mean a large number of species, each species in relatively low numbers.

Table 5. A summary of the biological structure in bodies of fresh water at various pH from below 3.5 to 7.0

RANGE	WARM WATER SPECIES	COLD WATER SPECIES	BENTHOS	MICROORGANISMS	ALGAE	PLANTS
6.5-7.0	Full fish production 2/	Full fish production	Relatively normal 1/, molluscs occur commonly	Small numbers of fungi; various bacterial species occur; microflora quite normal 1/	Essentially normal 1/	Normal 1/ flora
6.0-6.5	Maintenance and growth 3/	Full fish production				
5.5-6.0	Maintenance but no carry-over 4/	Maintenance and growth	Diverse fauna of benthic organisms; number of different species. Blackflies, mayflies and stoneflies are present in numbers	Yeasts and Thiobacillus-Ferrobacillus bacterial group are important; bacterial species diversity decreases	Diatoms, flagellates, and green algae are common; Oscillatoria may be found, only blue-green algae commonly occurring at pH lower than 7.0	Most aquatic plants will grow at this range if substrate, water velocity and fluctuations are satisfactory
5.0-5.5	No viable fishery 5/	Maintenance but no carry-over				
4.5-5.0	No viable fishery	No viable fishery	Little change	Bacteria Thiobacillus-Ferrobacillus group common yeast and fungi common component of microflora; bacterial species diversity decreases	Diatoms may be dominant algae; a decrease in number of different taxa	Cattails common; Eleocharis may be abundant
4.0-4.5	No viable fishery	No viable fishery	Caddisflies and Odonata are present; Tendipedids and chironomids are dominant	Similar to previous range except less bacteria	Number of different taxa decreases greatly; diatoms may be dominant algae, flora little changed from that of lower pH levels; microcrustaceans may be common	Little change
3.5-4.0	No viable fishery	No viable fishery	Little change	Little change	Little change	Cattail only common plant
below 3.5	No viable fishery	No viable fishery	Tendipedids, chironomids, ceratopogonids, and Sialis are common	Little change	Often only 2-3 algal species found; Euglena mutabilis and Eunotia exigura often found in large numbers; microcrustaceans may be common	Generally not found at this low of pH; cattails occur occasionally

Table 5 - Continued

1/ "Normal" is used here to mean a large number of species, each species in relatively low numbers.

2/ "Viable Fishery" -- capability of a stream to reproduce species.

3/ "Maintenance and growth" -- prevention of reproduction but allow existing fish population which occurs by stocking or migration, to survive and grow for entire year.

4/ "Maintenance but no carry-over" -- pollution level which allows fish maintenance by stocking, but no growth.

5/ "No Viable Fishery" -- pollution level which pre-empts vertebrate life but allows specialized invertebrate and plant survival.

The Effect of pH on Self-Purification of Domestic Wastes

Natural streams which are used for sewage treatment, if not overloaded and given enough time, will eventually break down and purify these wastes. Self-purification is largely dependent upon the activities of bacteria and other microorganisms. The growth and activity of these microorganisms are strongly affected by the pH of the environment. There are wide differences between the pH requirements of various species of microorganisms, but only a few are able to grow below pH 4 and above pH 9 (Klein, 1962). Reports on the effects of pH on biological treatment of sewage are numerous. Eckenfelder (1966) states that the effective pH range for most bio-oxidation systems are from 5 to 9, with optimum rates occurring at pH 6 to 8. Keefer and Meisel (1951) found that activated sludge can be acclimated to operate satisfactorily within the pH range 6 to 9. Above pH 10 reasonable operation is not possible. Similar results have been reported by many others.

In one of the earliest studies on the effect of acid mine drainage on sewage degradation, Carpenter and Herndon (1933) using acid mine waters of pH 2.0 found that in a mixture of 5 or 10% of this water and 90-95% of sewage effluent, a 90% reduction of the bacterial population occurred in one hour. After 3 hours, almost complete sterilization was achieved.

The effect of low pH on the self-purification of a river has been described by Chubb and Merkel (1946). The Schuylkill River in southeastern Pennsylvania received acid drainage from anthracite coal mines. The pH and dissolved oxygen content were measured along the river. In one stretch of the river, where the pH was about 4.5, the dissolved oxygen content increased from 5.8 ppm to 6.6 ppm after flowing for approximately 3 hours. An alkaline tributary raised the pH to about 6.5, a value which remained stable for about 3 hours flow downstream. The dissolved oxygen increase during this period was very small. Another alkaline tributary, receiving drainage from a limestone region, brought the pH of the river up to about 7.2. From this point on, rapid depletion of dissolved oxygen occurred. There was no addition of organic matter at this point, and it was therefore concluded that organic matter which had been carried by the river in a preserved or pickled state in the acid reaches of the river was now being oxidized by bacteria which could survive at this pH and which used oxygen at a rate exceeding the rate of re-aeration.

Another example has been described by Morgan (1942) on the upper Ohio River, which receives acid mine drainage and sewage. When the acid wastes were neutralized by dilution at high flows, the coliform count in the river averaged 5300 and reached a maximum of 37,000. At times of low flow, when the river was acid, the average count was 160 with a maximum of 700.

Joseph and Shay (1952) made longevity studies on the viability of Escherichia coli at pHs of 2.0, 2.5, 3.0, 3.5 and 4.0. Their results indicated a rapid reduction in numbers within the first 2 hours. Although acid mine drainage is lethal to E. coli, some coliforms survived after 24 hours at all pH's. As streams polluted with domestic wastes and acid mine drainage gradually increase in pH, a noticeable increase in the bacterial content is observed. Rogers and Wilson (1966) found essentially similar results in the laboratory when they exposed sewage microorganisms to various pH levels.

Sidio and Mackenthun (1963) also noted the inhibiting effect of acid conditions on bacteria. A creek with an average pH of 2.8 had virtually no coliform or fecal streptococci bacteria. A nearby creek with an average pH of 7.2 had an average coliform density of over 200,000/100 ml, and a fecal streptococci density of 6,500/100 ml. Both streams received sewage discharges.

As pH values increase toward neutrality, there is less inhibition of intestinal bacteria. At a certain station with a pH of 4.1, the coliform and fecal streptococci levels were less than 100 and less than 2 per 100 ml respectively. At the same station, 6 days later when the pH had increased to a pH of 5.4, the bacterial density increased to 23,000 coliform and 50,000 streptococci per 100 ml.

In laboratory tests using a synthetic sewage adjusted to pH levels of 7, 6, 5, 4, and 3.5, Rogers and Wilson (1966) found a direct correlation between pH and the number of organisms/ml. The higher the pH value, the larger the number of organisms/ml present. Using Monongahela River water (original pH of 6.5) adjusted to about the same pHs as above, the same positive correlation was observed between pH and bacterial flora.

In tests with raw sewage adjusted to different pHs, Wilson et al. (1964) found that different microflora complexes developed at pHs 7, 6 and 5.5 than at 3.5, 4 and 4.5. Microflora in slightly acid to neutral waters consisted of bacteria while at the strongly acid end these populations were largely yeasts.

The same authors (Wilson et al.) used the disappearance of sugars added to sewage adjusted to various pHs as a measure of sewage decomposition. The sugars were utilized quite rapidly at pH levels 7, 6 and 5.5 as compared to 3.5, 4 and 4.5. The rate of disappearance depended more upon the pH than the type of sugar.

Oxygen depletion was rapid in diluted sewage, with or without added sugars, at pH 7 but slow at pH levels between 3.5 and 4.0. Work by Cooke (1966) would indicate that at pH levels around 3.0, fungi are mainly responsible for BOD reduction in sewage. In fact, he found that BOD reduction at this pH occurred quite rapidly.

In addition to the effect of pH per se on microorganisms, substances toxic to the microflora are often affected by pH. Many metallic salts, for example, are more soluble under acid conditions and are therefore more toxic at low pH. The presence of dissolved heavy metal salts in concentrations that would be lethal or inhibiting to bacteria would decelerate the rate of sewage decomposition.

Thus, in summary, the effects of acid mine drainage on sewage degradation in streams are as follows: (1) a large reduction in the number of microorganisms in the sewage effluent. Some organisms survive including intestinal bacteria, even at pH 2. (2) the oxygen demand of the sewage is not exerted near the point of discharge, but delayed further downstream until the pH rises to favorable levels.

Thermal pollution and the ecological effects of low pH

The ready availability of fossil fuels and the large demands of power have made the regions adjacent to the Appalachians (especially in the northern-central reaches) attractive sites for power plants and for heavy industries which utilize large amounts of waters for cooling. There is already an acute awareness by biologists and the informed public of the deleterious biological effects of thermal effluents. The considerable amount of interest generated by this ecological disturbance has resulted in the creation of a large technical literature which will not be discussed here. There has been little consideration given specifically to the effects of thermal additions in water of low pH although there has been considerable discussion of the effects of temperature upon the toxicity of substances present in industrial and agricultural wastes.

It is known that increases in water temperature increase the toxic effect of most substances. The current literature regarding water quality in its relationship to aquatic organisms presents a good deal of quantitative toxicological data that can be used to evaluate the effects of thermal discharges on the toxicity of substances.

It is agreed by competent ecologists that even if the water temperature is only increased to a level well below the thermal death point of organisms, several events occur that increase the toxicity of most wastes. Fish and aquatic invertebrates are poikilotherms and react to increase in water temperature in a consistent manner. The metabolic activity of a fish increases as the water is warmed to a certain maximum. In order to supply the increased amounts of dissolved oxygen required to support the increased metabolism, the organism increases its respiratory activity. This results in an increase of water flow over the gills with a resultant greater exposure of the gills to the toxicants in the water. The effects on the fish can be crudely expressed as an "increased toxicity" in warmed waters, because the increased respiration brings the gills into contact with more toxicant. In addition, the toxicant may move more rapidly through the gill membranes from the water into the blood, and the toxicant will exert its lethal action more rapidly in the body of the fish. It is known that most substances are more lethal in warmer waters and although there is no data on the lethality of acids in warmer waters, there is no reason to expect that acids will not be more lethal at higher temperatures than in waters of the usual temperature.

Most installations that contribute thermal additions to water supplies are located on relatively large bodies of water where sufficient volumes of water are available for cooling. A survey of some of the available water quality literature on the Appalachians suggests that sufficient dilution is obtained in the lower stretches of streams so that the pH is usually above pH 5 or 6. Under the normal water temperatures, an interesting and useful even if restricted population of aquatic organisms might be maintained in waters of these pH. A significant increase in water temperature probably will have some deleterious effects on these populations. The increased respiratory activities and the increased flow of water past the gills will require the fish to work harder to maintain the buffer systems of their blood. Depending upon the water temperature and, of course, the pH, one could expect conditions ranging from a total loss of the more sensitive species to perhaps the retardation of growth of some if not most of the surviving species because of the increased demands for energy and nutrients to maintain the chemical characteristics of the blood. These nutrients would be required to allow the fish to maintain life and will not be available for growth.

There are reasonable arguments pro and con for the benefits or detriments of thermal pollution or thermal enrichment which have some basis in fact. The writers of this report cannot imagine that any benefits will accrue to an aquatic population in water of low pH that receives a thermal effluent.

Esthetics

There may be two major classes of fishermen. One class is the well-known "meat" fisherman who measures the success of his trip by the number of fish he brings home. The second-class includes the persons who use fishing as an excuse to get out-of-doors and who enjoys the esthetic experience of the pleasant surroundings which are usually associated with a fishing stream. The second fisherman is probably a good fisherman too. The first fisherman, of course, is repelled by the acid streams not only because of the rust-colored waters but because he knows there are no fish present. The second fisherman would not think of fishing in a visibly polluted stream even if fish production was good.

The hills and valleys of the Appalachians with their hardwood forests are recreational assets primarily because of their esthetic appeal and many would be happy in these hills if the scars of strip-mines were not visible. But many recreationists prefer water-based recreation in an appealing location, and those recreationists are going to avoid these polluted and scarred areas completely.

The typical acid stream bearing a heavy load of iron salts is characteristic in its unsightliness. The soluble iron salts at a pH of 3.0 or above become hydrated to form iron hydroxide or "yellow boy" which is carried by the stream as a colloidal floc in the more rapidly flowing areas or which settles out in the slower pools to coat the bottom. The yellow boy not only destroys the natural beauty and appeal but reduces the habitat for the aquatic invertebrates valuable as fish food.

In some streams with no iron salts, dense growths of algae develop which totally cover the bottom of the streams. These unrelieved masses of green which are usually of a single species, although more pleasant than deposits of yellow boy, are not an esthetic asset.

Perhaps the only pleasant aspect of some acid polluted bodies of water is their clarity, which is related to their unproductivity.

An acid stream draining the denuded and scarred hillsides as illustrated by Boccardy and Spaulding (1968) is a depressing sight. The restoration of the water quality of the streams would open a large recreational resource that would quickly be utilized by the recreation hungry populations of the most heavily populated portion of the United States.

A stream can support many more satisfied picnickers than it could support satisfied fishermen. The economic benefits derived from a water based recreation industry would be a positive value in the economics of a reclamation program.

Fishery Management Recommendations

(Management recommendations for full
fish production including completion
of all life history stages.)

The waters of the Appalachians can be roughly divided into those waters in which the water temperatures are cool enough to support trout (65°F and below) and the warmer waters (above 65°F) which are more suited for spiny ray fish such as bass and bluegills. In general, the waters of the Appalachian region are generally soft and are not regarded as highly productive waters. The native salmonid fauna is the brook trout although the rainbow has been introduced with varying success.

Fishery management emphasis should be placed upon a species that is desirable to sportsmen and recreationists and whose native habitat includes the Appalachians, or is similar to that of the Appalachians, and which, therefore, could be expected to thrive there if conditions either are or could be made suitable. As Lennon (Personal communication, 1959) has pointed out, the brook trout are more tolerant of acid waters than are the rainbow. A species should be utilized that could survive some brief episodes of acid water intrusion.

Economic considerations are very important, at least at the present time, when a primary consideration is the planning of a workable program to restore the acid waters, or at least some part of them, to biological productivity. Social and political considerations dictate that the maximum miles of stream be restored to productivity in a minimum time at a minimum cost. It stands to reason that at a certain cost, steps can be taken to restore a number of miles of stream to a pH of 6.0-6.5. It will certainly require a greater if not multiple cost to seal all the acid drainage sites to restore the pH of 7.0 or slightly above which is normal for the unpolluted streams. For example, one million dollars of engineering construction may give you 50 miles of productive brook trout water at a pH of 5.5 to 6.0, or the same funds may only give 10 miles of rainbow trout water, 6.0 to 7.0. Most fishermen will be just as happy and will spend as much money to capture a 7" brook trout as they would to capture a rainbow of the same size. Hence, reason dictates a program dedicated to attain water quality suitable for brook trout or for brown trout in slightly warmer waters, at least as a first step. Technological advances developed by research may open the way for the restoration of water quality to the normal for unpolluted streams in the more distant future.

There are some data (Lloyd and Jordan, 1964; Dahl, 1927) that indicate that eggs and yolk sac larvae of rainbow are affected adversely in water between pH 4.5 and 5.7. There are no laboratory data available to this writer that indicate the tolerance of the eggs and larva of brook trout to low pH. Lennon, in his personal communication (1959) suggests that successful reproduction of rainbow trout is restricted to waters of over pH 6.0 while eastern brook trout can reproduce if the water is pH 5.5 or perhaps slightly below. It is probable that a successful, reproducing Eastern brook trout population can be established if engineering and other abatement procedures can be conducted to maintain the waters at pH 6.0 and above. It is recommended, therefore, that after engineering procedures are completed to bring the streams to a pH of 6.0, that legal sized Eastern brook be planted in the cooler waters and brown trout be planted in the slightly warmer waters at a planting rate to be determined by qualified people in the state fish and game departments.

It will probably be necessary to repeat plants yearly, especially of Eastern brook trout, because if a sport fishery develops, natural reproduction will not be able to supply enough fish to sustain a desirable sport fishery. Annual plants are standard practice for almost all trout waters that are not in extremely remote areas.

Yet, in fact, it is hard to find a good economic justification for the maintenance of the pH of trout streams at a pH level that will allow natural production. Warner and others have demonstrated that a good mixed zoobenthos and periphyton exist at pH 4.5 and above. Eastern brook and brown trout will survive and grow well, as has been documented for many American and European streams, at pH 5.0 and above. It may be economical to bring the pH of a stream to 5.5 while it may not be economical to maintain the stream at 6.0 or 6.5. If we can make the assumption that trout will take a lure or fly at a pH of 5.5 as readily as they will at higher pH levels, (an assumption which may have no basis in fact) it may be best to plan to bring the stream to a pH 5.5 and rely entirely on planted fish. This may seem incongruous but we must remember in most states with large populations, trout fishing would be non-existent if it were not for the fish hatchery and the planting truck. In the Appalachians, especially in the Northern portions adjacent to the population centers, brook trout fishing would have to be supplied by the planting truck regardless if the pH is regulated at 5.5 or at 7.5. The recommended water standards (FWPCA (Anon, 1968)) for recreational contact sports (i.e. swimming and water skiing) call for a pH 6.5. Waters that meet the recommended interstate standards (FWPCA (Anon, 1968)) for all uses must be between pH 5.5 and pH 6.5, depending on the various states.

Hence, in summary, to meet interstate standards for all recreational water uses the pH must be 5.5-6.5. To insure the substantial natural reproduction of fish, the pH should be 6.5. To provide an adequate recreational fishery based upon planting of legal size fish the pH should be 5.5.

Recommendations for warm water fish management

There are probably more bass and pike fishermen than there are trout fishermen and many miles of water are suitable for warm water species. Consideration should be given to the management of these species. It has been the experience, however, that it is unnecessary to plant warm water fish species if even a small population of the desirable warm water species has access to the waters that may be rehabilitated. Although some pan fish (Lepomis) apparently can survive in water with a pH as low as pH 4.0, Shellgren's (1967) studies indicate that a good mixed fauna of fish is observed only at pH of 6.5 or higher. The impression is gained from Shellgren et al. (1967) that to maintain a warm water fish population the pH must be slightly higher than that necessary for an Eastern brook trout population. The economic problems involved in rehabilitating a stream for warm water species is considerably more grim because the waters suitable only for warm water fish populations are usually the larger streams which are usually lower in the watersheds, and much larger amounts of water therefore must be treated if a chemical treatment is deemed the appropriate action. On the other hand, the warmer waters may be the beneficiary of treatment or control procedures used in the upstream trout waters and one might expect the bonus of a resurgence of the spiny ray species assuming, of course, that the water quality is not disturbed by domestic and industrial wastes.

The problems involved in maintaining adequate populations of spiny ray fishes is simple compared to that of trout. It is not necessary usually to reintroduce a population of spiny rayed fishes. Reproduction is usually more than adequate to maintain population levels, the standing populations are large, and spiny rayed fishing is a less specialized fishery than the trout fishery. The number of fishing days generated by a spiny ray fishery is often greater than that of a trout fishery. A good spiny ray fishery can generate a larger expenditure of money with a minimum effort on the part of a conservation agency.

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Appendix I

One of the most important documents in regard to water quality is the Report of the National Technical Advisory Committee to the Secretary of the Interior entitled, "Water Quality Criteria," April 1, 1968, Federal Water Pollution Control Administration, Washington, D.C. Although the report of the committee was to offer guidelines useful for the establishment of water quality criteria in regard to interstate waters, the insights of this committee are of value to the Appalachian Regional Commission, in my judgment. The water quality parameters that protect the fish in the interstate rivers like the Ohio, pertain to the creeks and runs of the Appalachian highlands. The factors that make a large river pleasant for swimming also pertain to the swimming hole in a Pennsylvania or West Virginia stream.

The "Water Quality Criteria" committee was divided into several specialties according to the water use. Each of these major water uses was analyzed by a committee of specialists and each committee prepared its recommendations independently of each other. The pertinent recommendations of each special committee are quoted below:

Section I. Recreation and Aesthetics

C: Primary contact recreation

1. Criteria for mandatory factors
(page 4, Water Quality Criteria)

(b) In primary contact recreation waters, the pH should be within the range of 6.5-8.3, except when due to natural causes and in no case shall be less than 5.0 nor more than 9.0. When the pH is less than 6.5, or more than 8.3, discharge of substances which further increases unfavorable total acidity or alkalinity should be limited.

Section II. Public Water Supplies

Paragraph 14: pH
(page 23, Water Quality Criteria)

pH should be within the range of 6.5-8.3 except when due to natural causes and in no case shall be less than 5.0 nor more than 9.0. When the pH is less than 6.5, or more than 8.3, discharge of substances which further increases unfavorable total acidity or alkalinity should be limited

Section II. Public Water Supplies

Paragraph 14: pH
(page 23, Water Quality Criteria)

Most unpolluted waters have pH values within the range recommended as a permissible criterion. Any pH value within this range is acceptable for a public water supply. The further selection of a specific pH value within this range as a desirable criterion cannot be made.

Section III. Fish, other aquatic life, and wildlife freshwater organisms, pH, alkalinity, acidity
(page 32, Water Quality Criteria)

(1) No highly dissociated materials should be added in quantities sufficient to lower the pH below 6.0 or to raise the pH above 9.0.

(2) To protect the carbonate system and thus the productivity of the water, acid should not be added in sufficient quantity to lower the total alkalinity to less than 20 mg/l.

(3) The addition of weakly dissociated acids and alkalies should be regulated in terms of their own toxicities as established by bioassay procedures.

Section IV. Agricultural uses
pH (page 118, Water Quality Criteria)

Acidity or alkalinity as such in irrigation water is seldom detrimental to crop growth. Normally water with pH values of 4.5 to 9.0 should not present any insurmountable problems but a range of 5.5 to 8.5 would be more desirable.

Farmstead water supplies

(4) Non-corrosive waters
(page 121, Water Quality Criteria)

> Corrosion shortens the life of plumbing and water heaters. Copper and iron dissolved from piping by acid water may cause oxidized flavors in milk products.
>
> (page 124, Water Quality Criteria)
> pH
> It is recommended that the pH of milkhouse use fall between 6.8 and 8.5.
>
> Livestock water supplies
>
> Iron
> (page 136, Water Quality Criteria)
>
> Iron: Reports on direct toxicity resulting from iron in water are not available. However, it has been suggested that intake of water by livestock may be inhibited if it is high in iron.

It is observed that there is remarkable uniformity in the recommended pH limits for the various uses that are listed in Water Quality Criteria, especially in regard to low pH. Water that meets the pH criteria for fish will be suitable for swimming, agriculture, and farmstead water supplies. Abatement procedures that will create a suitable habitat for a good fish population will have the additional value of making the water suitable for many of the uses to which man assigns to water.

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