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Effects of Ambient pH on Fish: An Annotated Bibliography

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EFFECTS OF AMBIENT pH ON FISH: AN ANNOTATED BIBLIOGRAPHY

by

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ABSTRACT

Daye, P. G. 1980. Effects of ambient pH on fish: an annotated bibliography. Can. Tech. Rep. Fish. Aquat. Sci. 950, iii + 28 p.

An annotated bibliography on the effects of ambient pH on fish, consisting of 316 citations, is presented in alphabetical sequence according to author. These references are also cross-indexed by subject and geographical listings.

Key words: pH, fish, acid mine drainage, acid precipitation

RÉSUMÉ

Daye, P. G. 1980. Effects of ambient pH on fish: an annotated bibliography. Can. Tech. Rep. Fish. Aquat. Sci. 950, iii + 28 p.

Bibliographie annotée concernant les effets du pH ambiant sur les poissons, constituée de 316 mentions, présentée par ordre alphabétique des auteurs. Un index des sujets et des noms géographiques en facilite la consultation.

INTRODUCTION

This manuscript is an annotated bibliography of 316 publications that report effects of ambient pH on fish. In situations where the same paper has been presented at a conference, and/or published as an internal report, and also published in a primary journal, only the reference of the primary journal has been cited. Theses have been omitted from these references. Seventeen publications concerning effects of acid precipitation from Scandinavia, written in languages other than English that could not be obtained by the author and have been cited from Wright (1976). These references are followed with an asterix (*) in this manuscript.

The presentation of references is in alphabetical order according to author preceded by a corresponding sequential number and followed by a short abstract. The section of references by author is followed by a subject cross-reference section that categorically subdivides these references further under the headings, acclimation/discrimination/ preference; acid mine drainage; acid precipitation; biochemistry/physiology; combined effects; embryo/reproduction; growth; lethal levels; pathology; pollution; reclamation; reviews; and water quality. The section of subject references is followed by a geographic reference that includes specific studies pertaining to Canada, United States, Scandinavia, Europe and other countries. Cross references in both sections are by number.

It is the purpose of this manuscript to provide a comprehensive list of references concerning all aspects of the effects of ambient pH on fish. This manuscript will serve to give information and direction to research areas where deficiencies of data now exist.

ACKNOWLEDGMENTS

I thank Drs. R. H. Peterson and R. W. Elner for reviewing this manuscript.

1. Almer, B. 1972. Försuningens inverkan på fiskbestånd i västkustsjöar. Information från Sotvattens-Laboratoriet Drottningholm Nr. 12, 47 p.

Acidification of 50 surveyed Swedish lakes has resulted in drastic declines in fish fauna, especially roach, perch and arctic char. The roach has proved to be a fair indicator of acidification of a lake, since disturbances in roach reproduction are evident at a pH just below 5.5.

2. Almer, B. 1972. Ragnarök och fiskdöd. Svenskt Fiske, 12: 40-44. *

General discussion of the increasing acidification of Swedish lakes and rivers and the effects on fish, especially the phenomenon of large old fish that survive in acid lakes.

3. Almer, B., W. Dickson, C. Ekström, E. Hörnström, and U. Miller. 1974. Effects of acidification on Swedish lakes. Ambio 3: 30-36.

As a result of acidification, half of the lakes in the Swedish west coast region (about 1,500 of a total of 3,000) have pH values lower than 6.0, and 800-900 have pH values even lower than 5.0. A pH value below 5.8 will strongly affect aquatic life. The fish reproduction is affected. Roach, arctic char, trout, and perch have been eradicated from acidic waters.

4. Anderson, G., K. J. Gustafson, and T. Lindström. 1971. Rödingen i rösjöarna på fulufjäll. Information från Sötvattenslaboratoriet, Drottningholm 8, 9 p. *

Fish surveys and test fishing in several small acid lakes in Sweden show that acidification has altered the fish populations during the past 50 yr.

5. Anon. 1972. Guidelines for water qualities objectives and standards. A preliminary report. Inland Wat. Br., Dept. Environ., Ottawa, Can. Tech. Bull. No. 67.

The effects of pH on fish are discussed and guidelines for water quality are suggested.

6. Anon. 1977. Summary. The SNSF - project - acid precipitation - effects on forest and fish. Ann. Rep., SNSF-project, Norway, 48 p.

Research results in 1977 have strengthened earlier opinion that, historically, fish mortality follows a pattern. Starting with the combination of high addition of acid precipitation-low buffering ability in the watershed, the damaged area spreads gradually, usually downstream, in the water course.

7. Anthony, A., E. L. Cooper, R. B. Mitchell, W. H. Neff, and C. D. Therrien. 1971. Histochemical and cytophotometric assay of acid stress in freshwater fish. Water Pollut. Res. Series 18050 DXJ 05/71.

The primary role of acid toxicant action is gill damage which results in impaired respiratory, excretory and liver functions. Short-term indices of acid stress include: colloidal iron and PAS staining of gills and renal Stannius corpuscles. A useful bioindicator of prolonged acid exposure is decreased azure B-RNA staining of liver cells; this assesses the extent of liver impairment and reflects a reduced tolerance of fish to other toxicants.

Sublethal levels of acidity are not cumulative. However, pH levels of about 5.0 should be considered hazardous since they prove toxic to breeding fish having increased oxygen demands and reduce the liver's ability to detoxify noxious substances present in acid polluted waters.

8. Arillo, A., N. Maniscalco, C. Margiocco, F. Melodia, and P. Mensi. 1979. Fructose 1,6-bisphosphatase and total proteolytic activity in the liver of *Salmo gairdneri*: effects of pH and ammonia. Comp. Biochem. Physiol. 63C: 325-331.

An increase in environmental pH leads to similar though less marked effects than sublethal concentrations of un-ionized ammonia in the liver of rainbow trout. In the liver, changes occurred in the properties of fructose 1,6-bisphosphatase along with an increase in total proteolytic activity and free aminoacid concentration. It is suggested that changes in this gluconeogenic enzyme is a result of lysosomal proteases, which serve as an indicator of environmental stress.

9. Arillo, A., C. Margiocco, and F. Melodia. 1979. The gill sialic acid content as an index of environmental stress in rainbow trout, *Salmo gairdneri* Richardson. J. Fish Biol. 15: 405-410.

The gill sialic acid content is regarded as a biochemical factor which is extremely responsive to environmental changes. An abrupt rise in aqueous pH using sodium hydroxide resulted in increased levels of gill sialic acid concentration.

10. Baird, R., J. Bottomley, and H. Taitz. 1979. Ammonia toxicity and pH control in fish toxicity bioassays of treated wastewaters. Water Res. 13: 181-184.

Low flow O_2-aeration is the recommended method of controlling fish kills due to pH rise in static bioassay tests of effluents containing ammonia.

11. Baker, J. P., and C. L. Schofield. 1980. Aluminum toxicity to fish as related to acid precipitation and Adironack surface water quality. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Elevated levels of aluminum in surface waters affected by acidification appear to have serious effects on fish at pH levels above those which are normally considered harmful for most aquatic biota. Speciation of aluminum was shown to have substantial effect on aluminum toxicity to fish. The aluminum fraction chelated with organics is not toxic to fish.

12. Bandt, H. J. 1936. Der für fische "todliche pH-Wert" in alkalischem bereich. Z. Fisch. 34: 359-361.

Trout and perch died at pH 9.2, while roach, pike, carp and tench died at pH 10.4-10.8. The increased pH level was maintained by keeping water in contact with fresh blocks of cement.

13. Beamish, R. J. 1972. Lethal pH for the white sucker Catostomus commersoni (Lacépède). Trans. Am. Fish. Soc. 101: 355-358.

Lowering of pH below 4.5 caused cessation of feeding of the white sucker. Hydrochloric and sulfuric acid treatments resulted in similar median survival times. At lethal levels of pH below 4.0, fish developed a white film and could not be revived once this film developed. At pH 4.2 this film did not develop. Spinal deformities developed. It is suggested that the cause of death below pH 3.9 is different than those above.

14. Beamish, R. J. 1974. Growth and survival of white suckers (Catostomus commersoni) in an acidified lake. J. Fish. Res. Board Can. 31: 49-54.

White suckers in the acidic Lumsden Lake exhibited reduced annual growth followed by death. The reduced growth and death appeared directly related to the low pH and not to a shortage of food caused by the decreasing pH.

15. Beamish, R. J. 1974. Loss of fish populations from unexploited remote lakes in Ontario, Canada as a consequence of atmospheric fallout of acid. Water Res. 8: 85-95.

Fish populations in the study lakes were disappearing, primarily as a result of the high acid content of the lakes. As a lake became acidic, the more acid sensitive species ceased reproduction and eventually disappeared. The loss of fish populations resulted both from a long-term lethal effect and from an absence of recruitment of young into the population due to the failure of reproduction. In one of the lakes the acid levels have been high long enough to cause the loss of populations of even the most resistant species. Emissions from nickel smelters near Sudbury were the most probable source of contamination that has resulted in the loss of fish stocks from O.S.A., Muriel, and other lakes.

16. Beamish, R. J. 1976. Acidification of lakes in Canada by acid precipitation and the resulting effects on fishes. Water Air Soil Pollut. 6: 501-514.

In the Sudbury region of Ontario, Canada, fallout of sulfur oxides has been shown to be responsible for damage to vegetation, lakes and fishes. The acidic fallout has been shown to effect a rate of acidification in many lakes that over several decades has resulted in the extinction of many species of fishes. Fish exhibit profound differences in acid tolerance but show some similarities in their physiological response to levels within the range of their individual susceptibilities. Prior to extinction most females of a particular species did not release their ova to be fertilized. The failure of females to spawn was coincident with an inability to maintain normal serum Calcium levels. In some species growth was reduced despite an adequate supply of preferred food items. High concentrations of acid were considered to be the principal factor stressing the fish populations. Elevated concentrations of some heavy metals may add to the stress caused by high concentrations of acid.

17. Beamish, R. J., and H. H. Harvey. 1972. Acidification of the LaCloche mountain lakes, Ontario, and resulting fish mortalities. J. Fish. Res. Board Can. 29: 1131-1143.

The loss of populations of lake trout, lake herring, white suckers, and other fishes in Lumsden Lake was attributed to increasing levels of acidity within the lake. An absence of fishes was also observed in nearby lakes. In some lakes, acid levels have increased more than one hundredfold in the last decade. The increases in acidity appear to result from acid fallout in rain and snow. The largest single source of this acid was considered to be the sulfur dioxide emitted by the metal smelters of Sudbury, Ontario.

In 1971, pH measurements were taken from 150 lakes in the general study area 65 km southwest of Sudbury. Thirty-three of these lakes showed a pH of less than 4.5 and were described as "critically acidic." An additional 37 lakes had a pH in the range of 4.5-5.5 and were termed "endangered" lakes.

18. Beamish, R. J., W. L. Lockart, J. C. Van Loon, and H. H. Harvey. 1975. Long-term acidification of a lake and resulting effects on fishes. Ambio 4: 98-102.

In recent years the pH of George Lake has decreased at an estimated annual rate of approximately 0.13 pH units per year. Coincident with this, lake trout, walleye, burbot and smallmouth bass have disappeared and in 1973 northern pike, rock bass, pumpkinseed sunfish, brown bullhead and white suckers did not reproduce successfully. During the period 1967-73 the average size of white suckers declined drastically. The population of white suckers decreased from 934 mature fish in 1968 to 223 in 1973. The biomass of this species in 1973 was less than 10% of that measured in 1968. Spinal deformities first appeared in the white sucker population in 1971 and increased to 11% in the spring of 1972 and 32% by the fall of 1972. It appeared that the increased percentage of deformities was related to a decrease in pH below 5.0. In 1972 and 1973 white suckers and some other species had abnormal concentrations of calcium in their serum during the period of ovarian maturation. While a direct causal relationship between the increased acid content of the lake and the disturbances in calcium metabolism was not demonstrated in this study, it was suggested that a change in normal calcium metabolism was induced by low pH values and the abnormal serum calcium values may be related to the failure of fishes to spawn.

19. Belding, D. L. 1927. Toxicity experiments with fish in reference to trade waste pollution. Trans. Am. Fish. Soc. 57: 100-119.

A general paper on the effects of specific pollutants on fish. Behavior of fish in specific acids and alkalies is described.

20. Bell, G. R., G. E. Hoskins, and J. W. Bagshaw. 1969. On the structure and enzymatic degradation of the external membrane of the salmon egg. Can. J. Zool. 47: 146-148.

Chum salmon hatching enzyme has an optimum pH of 7.5-8.0 for the release of soluble peptides from the radiate membrane and requires metal ions for activity.

21. Bengtsson, B., W. Dickson, and P. Nyberg. 1980. Liming acid lakes in Sweden. Ambio 9: 34-36.

Liming is discussed as a method of keeping fish populations alive in poorly buffered acidified lakes.

22. Berzins, B. 1966. Kalkning av sjöar. Södra sveriges fiskeriförening 1959-1966: 28-35. *

Liming of lakes in southern Sweden has increased their pH levels, growth of phytoplankton and survival of salmonids.

23. Bhaskara Haranath, V., P. Reddenna, and S. Govindappa. 1978. Effect of exposure to altered pH media on tissue proteolysis and nitrogenous end products in a freshwater fish Tilapia mossambica (Peters). Ind. J. Exp. Biol. 16: 1088-1090.

Ammonia and urea levels were increased in liver of fish exposed to basic and acidic media, respectively. A pH dependent flexibility in the pattern of nitrogen excretion is suggested.

24. Bishai, H. M. 1960. The effect of hydrogen ion concentration on the survival and distribution of larval and young fish. Z. wiss. Zool. 164: 107-118.

The author used CO_2 to lower the pH and $NaHCO_3$ to raise the pH of the test water. The lower incipient limiting levels of pH are reported to be 6.49-6.6, 6.8, and 6.15-6.5, for Clupea harengus, Cyclopterus lumpus, and Pleuronectes platessa, respectively. The lower incipient pH limiting level for Salmo salar L., S. trutta L., and S. trutta F. fario is pH 6-6.2. The upper incipient limiting pH level for salmonid alevins is pH 9.

25. Boccardy, J. A., and W. M. Spaulding. 1968. Effects of surface mining on fish and wildlife in Appalachia. Bur. Sport Fish. Wildl. Resource Publ. 65, 20 p.

Surface mining has caused extensive damage to fish habitats and populations. More than 5,000 mi of Appalachian streams have been seriously contaminated by acid mine water.

26. Borgstrom, R., and G. R. Hendrey. 1976. pH tolerance of the first larval stages of Lepidurus arcticus (Pallas) and adult Gammarus lacustris G.O. Sars. SNSF Project IR 22/76, 37 p.

Short-term acidification below pH 5.5, often observed during spring snow melting, can eliminate G. lacustris and L. arcticus from small lakes. This may be expected to have negative effects on fish populations because of their importance as fishfood.

27. Börjeson, H., and A. Aldberg. 1974. Buffertkapacitet och pH i mjölke från två övingsstammar. Information från Sötvattenslaboratoriet, Drottningholm No. 3, 6 p. *

Trout from lakes in the Kloten area, Sweden, live near their lower pH-tolerance limit. No chemical difference in the milt from this stock and a reference stock could be found.

28. Brown, D. J. A., K. Sadler, G. D. Howells, and A. S. Kallend. 1980. Fish and freshwater chemistry. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Relationships of observed patterns of acidity and fishery status were reviewed, distinguishing progressive long-term responses of fish populations from acute responses to short term incidents.

29. Brown, H. W., and M. E. Jewell. 1926. Further studies on the fishes of an acid lake. Trans. Am. Micro. Soc. 45: 20-34.

Fishes can survive abrupt transference in waters ranging pH 8.6-4.4 in either direction.

30. Brungs, W. A., R. W. Carlson, W. B. Horning, J. H. McCormick, R. L. Spehar, and J. D. Yount. 1978. Effects of pollution on freshwater fish. J. Water Pollut. Control Fed. 50: 1582-1637.

A literature review of 1977 research.

31. Brungs, W. A., J. H. McCormick, T. W. Neiheisel, R. L. Spehar, C. E. Stephan, and G. N. Stokes. 1977. Effects of pollution on freshwater fish. J. Water Pollut. Control Fed. 49: 1425-1493.

A literature review of 1976 research.

32. Bua, B., and E. Snekvik. 1972. Klekkeforsøk med rogn av laksefisk 1966-1971. Virkning av surhet og saltinnhold i Klekkevannet. Vann 7: 86-93.

Results indicate that the critical limit for Atlantic salmon, sea trout and lake trout is pH 5.0-5.5, 4.5-5.0, and 4.5, respectively.

33. Bull, H. O. 1940. Studies on conditioned responses in fishes. IX. Discrimination of changes in hydrogen-ion concentration by marine teleosts. Rep. Dove Mar. Lab., 3rd Ser. 7: 21-31.

Twenty species of marine teleosts were able to discriminate a reduction of between 0.04 and 0.06 in the pH of seawater by the addition of CO_2.

34. Butler, R. L., E. L. Cooper, J. K. Crawford, D. C. Hales, W. G. Kimmel, and C. C. Wagner. 1973. Fish and food organisms in acid mine waters of Pennsylvania. Ecol. Res. Ser. Publ. No. EPA-R3-73-032, 158 p.

There was no relationship between cover utilization and pH levels or between fish activity and pH levels.

Common fish species in Pennsylvania watersheds were absent where there was severe acid mine drainage. Of 116 species of fish in Pennsylvania, 10 were present in waters of pH 5.5 or less. An additional 38 species were found in waters ranging pH 5.6-6.4. The remaining 68 species were present only in water above pH 6.4.

35. Cairns, J., T. K. Bahns, D. T. Burton, K. L. Dickson, R. E. Sparks, and W. T. Waller. 1971. The effects of pH, solubility and temperature upon the acute toxicity of zinc to the bluegill sunfish (Lepomis macrochirus Raf.). Trans. Kansas Acad. Sci. 74: 81-92.

Bluegill mortalities to soluble zinc were greater at low pH (5.7-7.0) than at high pH (7.3-8.8).

36. Cairns, J., J. S. Crossman, K. L. Dickson, and E. E. Herricks. 1971. The recovery of damaged streams. ASB Bull. 18: 79-106.

Short-term acute stresses produced by the release of acidic or caustic materials into a receiving stream elicit a response in fish communities typified by an immediate reduction in the number of individuals.

37. Cairns, J., K. L. Dickson, and J. S. Crossman. 1972. The response of aquatic communities to spills of hazardous materials. Proc. 1972 Nat. Conf. Hazardous Materials Spills, 179-197.

An Appalachian power plant accidently released an undetermined amount of sulfuric acid which killed about 5,300 fish and caused stream damage for 13.5 river miles.

In 1967, a fly ash pond spill into the Clinch River in the Appalachian Mountains caused numerous fish deaths and reduced fish food organisms for 77 mi downriver from the spill.

38. Calabrese, A. 1969. Effects of acids and alkalies on survival of bluegills and largemouth bass. U.S. Bur. Sport Fish. Wildl. Tech. Pap. 42, 10 p.

It is concluded that pH manipulation is impractical as a method for selectively thinning bluegills from bass-bluegill populations in farm ponds because of their slight differences in pH tolerances.

39. Campbell, R. N. 1961. The growth of brown trout in acid and alkaline waters. Salm. Trout Mag. 161: 47-52.

There appears to be no correlation between pH value and growth rate of brown trout in nine Scottish lakes.

40. Carrick, T. R. 1979. The effect of acid water on the hatching of salmonid eggs. J. Fish Biol. 14: 165-172.

There were no marked differences among Atlantic salmon, sea trout and brown trout in the tolerances of their eggs to acid water; pH 3.5 was lethal within 10 d to all eggs, but at pH 4.5 and higher there was no obvious difference in hatching attributable to acidity.

41. Carrithers, R. B., and F. J. Bulow. 1973. An ecological survey of the west fork of the Obey River, Tennessee with emphasis on the effects of acid mine drainage. J. Tenn. Acad. Sci. 48: 65-72.

The number of fish species and total number of individuals in the west fork of the Obey River were reduced as a result of acid mine drainage from the upstream Cub Creek.

42. Carter, L. 1964. Effects of acidic and alkaline effluents on fish in seawater. Effluent Water Treat. J. 4: 484-486.

Fish mortalities are unlikely if the pH of seawater lies within the range from pH 5.5-9.0. Rainbow trout that survived pH 4.9 in seawater had exopthalmia and were blind.

43. Chróst, L., and L. Pinko. 1980. The effect of calcium on the toxicity of zinc and lead compounds in the water medium. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

The toxicity of zinc and lead at varying pH values is lowered in the presence of increased calcium concentrations.

44. Clowes, G. H. A., and H. W. Smith. 1923. The influence of hydrogen-ion concentration on the fertilization and growth of certain marine eggs. Am. J. Physiol. 64: 144-159.

pH and not CO_2 affects the cortical fertilization process of certain marine eggs.

45. Coker, R. E. 1925. Observations of hydrogen-ion concentration and of fishes in waters tributary to the Catawba River, North Carolina (with supplemental observations in some waters of Cape Cod, Massachusetts). Ecology 6: 52-65.

In the waters examined, centrarchids inhabited alkaline waters generally, while brook trout inhabited acid or neutral waters.

46. Conroy, N., and L. Maki. 1974. Extensive and intensive lake studies in the Sudbury area, p. 138-143. In Ontario Industrial Wastes Conferences 1974.

The biological dynamics of lakes are reduced as pH declines and heavy metals become more abundant to the point that entire fisheries can be destroyed.

47. Craig, G. R., and W. F. Baksi. 1977. The effects of depressed pH on flagfish reproduction, growth and survival. Water Res. 11: 621-626.

Results indicate a "no effect" level of pH depression for successful reproduction of the flagfish to be pH 6.5. Reduction in the reproductive processes monitored indicated the following order of sensitivity: egg production > fry survival > fry growth > egg fertility.

48. Crandall, C. A., and C. J. Goodnight. 1959. The effect of various factors on the toxicity of sodium pentachlorophenate to fish. Limnol. Oceanogr. 4: 53-56.

The toxicity of sodium pentachlorophenate to fathead minnows increased with lower levels of pH.

49. Creaser, C. W. 1930. Relative importance of hydrogen-ion concentration, temperature, dissolved oxygen and carbon-dioxide tension, on habitat selection by brook trout. Ecology 11: 246-262.

The range of voluntary toleration by brook trout extends at least from pH 4.1-9.5. It was concluded that it was not possible to distinguish suitable brook trout waters on the basis of their pH. There was no indication that either acid or alkaline waters were more favorable or more generally preferred by brook trout. Variation of the hydrogen-ion concentration over this range seems to have little or no influence upon the temperature or dissolved oxygen limits preferred by brook trout.

50. Creaser, C. W., and H. W. Brown. 1927. The hydrogen-ion concentration of brook trout waters of northern lower Michigan. Ecology 8: 98-105.

Brook trout were found to be abundant and completing their entire life history in waters of distinct alkalinity. It was concluded that the hydrogen-ion concentration had little effect on the toleration of brook trout for a given habitat. Temperature appeared to be a more overriding factor.

51. Crisman, T. L., R. L. Schulze, P. L. Brezonik, C. D. Hendrey, and S. A. Bloom. 1980. The biotic response in Florida lakes. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Preliminary data on fish populations suggest that species replacements associated with acidification of temperate systems may not be as severe in subtropical Florida systems as a result of the low Al^{+3} concentrations in the latter lakes.

52. Crissman, H. A., and C. D. Therrien. 1969. Cytochemical analysis of liver histones in acid exposed brook trout. Proc. Pa. Acad. Sci. 43: 49-52.

Exposure of brook trout to low pH did not affect the relative proportions of three spectrally distinct cell types of the liver indicating that this aspect of liver function is not influenced by short exposure to low pH.

53. Crissman, H. A., and C. D. Therrien. 1970. Spectrophotometric and electrophoretic analyses of DNA and histones in liver parenchymal nuclei of acid-exposed brook trout. Proc. Pa. Acad. Sci. 44: 57-61.

No quantitative change in nuclear DNA or histone in the liver of brook trout occurs with short-term exposure to low pH. Qualitative differences in the arginine-rich histones of the liver are suggested.

54. Dahl, J. 1963. Transformation of iron and sulphur compounds in soil, and its relation to Danish inland fisheries. Trans. Am. Fish. Soc. 92: 260-264.

Increased lignite mining and land reclamation in Denmark since 1940 have resulted in many fish kills and loss of fish habitats. The oxidation of pyrite exposed in lignite strip mining or in drainage of peat bogs results in sulphuric acid and ferric sulphate, which kills fish when washed into streams, lakes or ponds.

55. Dahl, K. 1923. Massedød blant ørret ved forgiftning med avløpsvand fra myrer. Norges Jaeger and Fisk. for. Tidsskr. 52: 1-5. *

Fish kills in southern Norway in 1920 are ascribed to accumulations of sulfuric and nitric acids in bogs during the dry summer followed by flushing during heavy rains.

56. Dahl, K. 1926. Vandets surhetsgrad og deres virkninger på ørretyngel. Tidsskr. norske Landbr. 232-242. *

The effect of acidity on trout spawning success from several lakes and streams in southern Norway is discussed.

57. Dahl, K. 1927. The effects of acid water on trout fry. Salm. Trout Mag. 46: 35-43.

A decrease in the "health" of trout fry in hatcheries in southwestern Norway occurred when the pH dropped below 6 and approached 5.5. Some mortalities occurred when the pH was lowered to 5.1. Serious or even total mortality of trout fry may occur when pH drops below 5.

58. Dannevig, A. 1959. Nedbørens innflytelse på vassdragenes surhet og på fiskebestanden. Jaeger og Fisker 3: 116-118. *

This is an early report linking acid rain to acidity of fresh waters and thence to fish kills.

59. Dannevig, G. 1966. Auren og det sure vannet på Sørlandet. Norg. Jeg. og Fiskerforb. Tidsskr. 388-393. *

The author reports that some strains of trout are more resistant to acid-stress than others. These resistant strains may perhaps be used for stocking low-pH lakes in southern Norway.

60. Dannevig, G. 1968. Surt vann og dødelighet på ørret. Zool. Revy (Sverige) 30: 53-60. *

The disappearance of trout from many lakes and rivers in southern Norway is due to increasing acidity of the waters. Breeding, hatching and survival of fry are decreased at low pH. Some local stocks are more acid resistant than others.

61. Dannevig, G., B. Kjos-Hansen, K. W. Jensen, and E. Snekvik. 1971. Fiskebestand og forsurning av vassdrag. Jakt. fiske. friluftsliv 100: 149-151, 198-201. *

The increase in acidity of precipitation in southern Norway during the last 20 yr has caused drastic increases in the acidity of thousands of lakes and rivers and the consequent loss of fisheries.

62. Daugherty, A. M., and L. C. Altman. 1925. Influence of hydrogen ion concentration, salinity and oxygen upon the rheotaxis of some marine fishes. Publ. Puget Sound Biol. Sta. 3: 365-368.

The rheotaxis of salmon is affected by increased hydrogen ion concentration and to a slight extent by reduced hydrogen ion concentration.

63. Davies, W. D. 1973. The effects of total dissolved solids, temperature, and pH on the survival of immature striped bass: A response surface experiment. Prog. Fish-Cult. 35: 157-160.

This study suggests that survival of hatchery-reared striped bass fry could be improved if close attention was paid to controlling levels of temperature, pH, and total dissolved solids.

64. Daye, P. G. 1980. Attempts to acclimate embryos and alevins of Atlantic salmon, Salmo salar, and rainbow trout, S. gairdneri to low pH. Can. J. Fish. Aquat. Sci. 37: (in press).

Acclimation to low pH as judged by the lack of resistance adaptation did not occur. Alevins had 10,000 min LL50's for pH of about 4.3 for four strains of salmonids and were less tolerant than embryos.

65. Daye, P. G., and E. T. Garside. 1975. Lethal levels of pH for brook trout, Salvelinus fontinalis (Mitchill). Can. J. Zool. 53: 639-641.

Lethal limits of pH for brook trout were about pH 3.5 and 9.8. The order of death was not significant in relation to length or weight of the fish from the same age group.

66. Daye, P. G., and E. T. Garside. 1976. Histopathologic changes in surficial tissues of brook trout, Salvelinus fontinalis (Mitchill), exposed to acute and chronic levels of pH. Can. J. Zool. 54: 2140-2155.

Thresholds for tissue and cellular derangements were pH 5.2 and 9.0. Mucus cells of gills, nares, and integument exhibited progressive degrees of hypertrophy and excessive secretion of mucus with increased pH stress. Epithelial necrosis and sloughing occurred extensively on gills, corneae, and integument. At the lethal levels (pH 3.5 and 9.8), epithelial necrosis also occurred in the esophagus. No cellular injury was detected in the stomach or any part of the intestine.

67. Daye, P. G., and E. T. Garside. 1977. Lower lethal levels of pH for embryos and alevins of Atlantic salmon, Salmo salar L. Can. J. Zool. 55: 1504-1508.

Sensitivity of Atlantic salmon embryos and alevins to low pH was dependent on the stage of development. Alevins were more sensitive to low pH than embryos. Embryos in early cleavage were more sensitive to low pH than older encapsulated embryos. Lethal levels of pH 3.6, 3.0 and 4.0 were determined for embryos in early cleavage, embryos just prior to hatch, and alevins, respectively.

68. Daye, P. G., and E. T. Garside. 1979. Development and survival of embryos and alevins of the Atlantic salmon, Salmo salar L., continuously exposed to acidic levels of pH, from fertilization. Can. J. Zool. 57: 1713-1718.

Atlantic salmon embryos had an LL50 of pH 3.9. The rate of embryonal development was not altered by pH. The LL50 for alevins was pH 4.3. Externally deformed alevins were few and not related in frequency to particular levels of pH. Populations of Atlantic salmon will decline and ultimately disappear from freshwater habitats whenever the level of pH approaches 4.5 for an extended period.

69. Daye, P. G., and E. T. Garside. 1980. Structural alterations in embryos and alevins of the Atlantic salmon, Salmo salar L., induced by continuous or short-term exposure to acidic levels of pH. Can. J. Zool. 58: 27-43.

Sublethal alterations occurred in the integument, gill, blood and blood vascular structures of all live alevins incubated at pH 5.0 and lower. At pH 4.5 and lower, injuries also occurred in the brain, optic retina, kidney and spleen. Some tissue regeneration occurred in the embryonal rudimentary integument at pH 4.5 and lower. Regeneration also occurred but to a lesser degree in pseudobranch, kidney, spleen and erythrocytes. Injury of the integument was the apparent cause of death in prehatching embryos since it is the major site of respiration and ion exchange. As gills expand in posthatching alevins, they assume these functions and destruction of branchial epithelium then becomes the prime cause of death. The nature of cell injury and consequent dysgenesis at tissue and organ levels are not ascribable uniquely to acidic stress.

70. Daye, P. G., and E. T. Garside. 1980. Development, survival and structural alterations of embryos and alevins of Atlantic salmon, Salmo salar L., continuously exposed to alkaline levels of pH, from fertilization. Can. J. Zool. 58: 369-377.

Developmental processes and hatching were not affected at pH 9.0 or 9.5. Embryo mortalities at pH 9.0 and 9.5 were similar to controls at pH 6.8. There was an accelerating increase in cumulative alevin mortality to 18% at pH 9.5 by 50 d after hatching, the end of the experiment.

Sublethal changes in embryos were confined mostly to cell necrosis and sloughing of the rudimentary epidermis. Some metaplasia of the brain stem occurred at pH 9.5. Sites and intensity of alterations increased in alevins at pH 9.5, following the loss of the zona radiata. In addition to ongoing injury of epidermis, including mucus cells, deleterious alterations occurred in branchial epithelium, erythrocytes, myocardium, blood vessels of the viscera, liver, brain and optic lenses. In general, sublethal changes caused by hydroxyl ions were similar to those caused by excessive hydrogen ions but were somewhat less extensive in the structures affected or in their degree of severity.

71. Dazarola, G., R. Labat, and J. Kugler. 1973. Influence de la température et du pH du milieu ambiant sur l'électrocardiogramme et les mouvements operculaires chez la carpe et la tanche. Ann. Limnol. 9: 63-77.

The physiological reactions of carp and tench are affected more strongly by temperature variations than by pH or the combined action of these two factors. A temperature of 25°C is the critical maximum above which the action of the parasympathetic nervous system is found to be modified. The acid environment inhibits cardiac activity and accelerates respiratory frequency in the carp; this action is perhaps due to an oxygen deficit caused by a fall in blood pH.

72. Dickson, W. 1975. The acidification of Swedish lakes. Rep. Inst. Freshw. Res. Drottningholm 54: 8-20.

A comprehensive review of Swedish lakes and their acidification.

73. Dively, J. L., J. E. Mudge, W. H. Neff, and A. Anthony. 1977. Blood P_{O_2}, P_{CO_2} and pH changes in brook trout (Salvelinus fontinalis) exposed to sublethal levels of acidity. Comp. Biochem. Physiol. 57A: 347-351.

Brook trout exposed to sublethal acid levels had elevated P_{CO_2}, hematocrit and ventilation rates. Neither hypoxemia nor blood acidosis was evidenced.

74. Dochinger, L. S., and T. A. Seliga (Editors). 1976. Proc. First Int. Symp. Acid Precipitation and the Forest Ecosystem. U.S. Dept. Agric. Forest Serv. Gen. Tech. Rep. NE-23, 1074 p.

These proceedings contain papers on acid rain.

75. Dolsky, M. F., and A. Anthony. 1973. Histochemical analysis of prolactin and Stannius corpuscle cells of brook trout exposed at low pH. Proc. Pa. Acad. Sci. 47: 123-125.

Cytopathological studies were conducted on pituitary prolactin and renal Stannius corpuscle cells of brook trout exposed to pH 4.4. Cytophotometric measures of RNA and protein indicate increased levels of these compounds in Stannius corpuscle cells after 2 d of acid stress, while prolactin cells exhibit decreased levels of RNA. However, RNA and protein levels of prolactin cells increased over control levels after 3 d of exposure when there was maximum skin mucification. These histochemical changes in prolactin and Stannius corpuscle cells after exposure to acid stress suggest an osmoregulatory role of these cells in freshwater fish.

76. Doudoroff, P. 1957. Water quality requirements of fishes and effects of toxic substances, p. 403-430. In The Physiology of Fishes (M. E. Brown, ed.), Vol. 2. Academic Press, N.Y.

A brief summary of the role of pH on the water quality requirements of fishes generally.

77. Doudoroff, P., and M. Katz. 1950. Critical review of literature on the toxicity of industrial wastes and their components to fish. I. Alkalies, acids, and inorganic gases. Sewage Industr. Wastes 22: 1432-1458.

An early review of the literature.

78. Drabløs, D., and I. Sevaldrud. 1980. Lake acidification, fish damage and utilization of outfields. A comparative survey of six highland areas in Hedmark County, eastern Norway. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Slight acidification during the last 10-25 yr has occurred in these lakes but it has not been related to land use changes in the outfields. Increasing fish losses have been reported here since mid-1970's.

79. Drummond, R. A., G. F. Olson, and A. R. Batterman. 1974. Cough response and uptake of mercury by brook trout, Salvelinus fontinalis, exposed to mercuric compounds at different hydrogen-ion concentrations. Trans. Am. Fish. Soc. 103: 244-249.

The lowest concentration of methylmercuric chloride (MMC) and mercuric chloride added to Lake Superior water that caused a significant increase in cough frequency in brook trout was 3 μg Hg/L. Cough frequency is a good short-term indicator of the long-term effects of MMC. The response can be used to predict the safe concentration of mercuric chloride. Increases in cough frequency were proportional to the concentration (from 3-12 μg Hg/L) of both compounds at pH 7.5. The fish were more responsive to MMC when the pH of the test water was lowered to 6.0; response to mercuric chloride was not changed by lowered pH. Fish exposed to MMC at pH 6.0 contained more total mercury in their gills and red blood cells than fish tested at pH 9.0. The uptake of mercury by brook trout exposed to mercuric chloride did not differ significantly at pH 6.0 and 9.0.

80. Dunson, W. A., and R. R. Martin. 1973. Survival of brook trout in a bog-derived acidity gradient. Ecology 54: 1370-1376.

Bear Meadows Bog water has a pH of 3.7-4.7 and is devoid of fish. Brook trout and white suckers do exist 5.2 km below the bog where the pH is about 4.75. Survival times of hatchery brook trout placed downstream from the bog were directly related to pH. Individual differences in tolerance to low pH were quite marked.

81. Dunson, W. A., F. Swarts, and M. Silvestri. 1977. Exceptional tolerance to low pH of some tropical blackwater fish. J. Exp. Zool. 201: 157-162.

Cardinal, neon, and emperor tetras, small South American characin fish are often found in acidic blackwater rivers. The lower incipient LL50 for pH is about 3.35 for neon and cardinal tetras. Both guppies and tetras lose large amounts of body sodium on exposure to lethal pH's.

82. Eddy, F. B. 1976. Acid-base balance in rainbow trout (Salmo gairdneri) subjected to acid stresses. J. Exp. Biol. 64: 159-171.

Rainbow trout were acid stressed by either acid injection into the bloodstream or by increasing the CO_2 content of the ambient water. Some differences were noted in the response and compensation to the acidosis. In each experiment the blood P_{O_2} was little changed but blood O_2 content was decreased and tended not to reach the control value even after several hours.

83. Edwards, D., and T. Gjedrem. 1979. Genetic variation in survival of brown trout eggs, fry and fingerlings in acidic water. SNSF-project, Norway FR 16/79, 28 p.

Brown trout were tested for survival of eggs before eyeing, eyed eggs, and alevins up to swim-up, in water of pH 4.7, 5.2 and 6.2. Underyearling brown trout were tested for survival time in water of pH 2.5, 3.0 and 4.0. Analyses of variance revealed highly significant differences in mortality and survival time between fish strains, and between sires within strains. Heritability estimates for these strains varied between 0.0 and 0.33. The results indicate good prospects for improvement through selective breeding. Inter-strains crosses showed mean survival rates twice as high as their parental strains. Regression of fish survival time on temperature was highly significant.

84. Edwards, D. J., and S. Hjeldnes. 1977. Growth and survival of salmonids in water of different pH. SNSF-project, Norway, FR 10/77, 12 p.

One-year-old rainbow trout, brown trout, and Arctic char were grown in tanks for 3½ mo in water at pH levels 4.8-5.0, 5.5 and 6.1-6.2. All fish received excess food. No difference in growth was found between fish kept at the upper two pH levels, but rainbow trout and Arctic char in water at pH 4.8 gained significantly less weight and length. At the end of the experiment no differences were found in blood plasma sodium content, but fish kept in water at pH 6.1 had significantly higher plasma potassium than the other two groups. Tests of survival time at lethally low pH showed that brown trout survived best, Arctic char intermediate, and rainbow trout poorest. Within species no correlation was found between fish size and survival time, or between previous pH history and survival time, i.e. there was no acclimation.

85. Eicher, G. J. 1946. Lethal alkalinity for trout in waters of low salt content. J. Wildl. Mgt. 10: 82-85.

Alkalinity has been found to be a highly lethal factor for trout in Arizona waters low in buffering agents. Trout were killed under certain conditions by a pH of 8.8, while under other conditions survived a pH of 10.2.

86. EIFAC (European Inland Fisheries Advisory Commission Working Party). 1969. Water quality criteria for European freshwater fish: Extreme pH values and inland fisheries. Water Res. 3: 593-611.

A summary on the effect of pH values on fish.

87. Eisler, R. 1970. Factors affecting pesticide-induced toxicity in an estuarine fish. Bur. Sport Fish. Wildl. Tech. Pap. 45, 20 p.

Temperature, salinity, and pH of the medium all influence pesticide-induced mortality. The toxicity of organophosphorus insecticides to mummichogs was inversely proportional to pH in the range 5.5-10. Toxicity of organochlorine insecticides to mummichogs was least at intermediate pH (7-8) within the ranges tested.

88. Ellis, M. M. 1937. Detection and measurement of stream pollution. U.S. Bur. Fish. Bull. 48: 365-437.

10,000 readings of inland streams of the United States, southern Canada, and northern Mexico taken from 1930-35 ranged from pH 6.7-8.6 with extremes of pH 6.3 and 9.0 in streams with no specific pollution. Swamps and bogs did have values from pH 4.5-6.0. Lethal limits of many stream pollutants are given.

89. Epler, P. 1971. Oddzialywanie zanieczyszczenia wod na ich ichtiofaune: IV. Toksycznosc kwasow i zasad oraz niektorych gazow nieorganicznych. Postepy Nauk Roln. 18: 85-102.

Acids produce free CO_2 which is lethal to fish in water with a high bicarbonate content. Resistance times at low pH varies with age of trout. pH 10.0 is lethal to most fish and pH levels below 4.0 are also generally toxic.

90. Falk, D. L., and W. A. Dunson. 1977. The effects of season and acute sublethal exposure on survival times of brook trout at low pH. Water Res. 11: 13-15.

A marked seasonal decline in survival times of brook trout was obtained between December and February. Heritable differences in acid tolerance of some inbred strains of brook trout were large.

91. Fleischer, S. 1980. The river Hogvadsån liming project - a presentation. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

This river system has the most important breeding areas for the salmon on the west coast and has now become severely acidified. This river now has probably the world's largest liming project. Details of liming and difficulties are discussed.

92. Franzin, W. G., and G. A. McFarlane. 1980. Fallout, distribution and some effects of Zn, Cd, Cu, Pb and As in aquatic ecosystems near a base metal smelter on Canada's precambrian

shield. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

White suckers in lakes contaminated by base metals from atmospheric fallout had poorer spawning success, lower recruitment, reduced longevity, and smaller egg size than white suckers living in uncontaminated lakes.

93. Freeman, R. A., and W. H. Everhart. 1971. Toxicity of aluminum hydroxide complexes in neutral and basic media to rainbow trout. Trans. Am. Fish. Soc. 100: 644-658.

Toxicities of various concentrations of aqueous aluminum complexes to rainbow trout were highly pH dependent.

94. Fromm, P. O. 1980. A review of some physiological and toxicological responses of freshwater fish to acid stress. Environ. Biol. Fish. 5: 79-93.

This is a review paper.

95. Frost, W. E. 1939. River Liffey survey - 2. The food consumed by the brown trout (Salmo trutta L.) in acid and alkaline waters. Proc. R. Ir. Acad. (B) 45: 139-206.

Brown trout of the fresh waters of Ireland may be roughly divided into two categories, small, slow-growing fish found in acid water derived from non-lime-bearing rocks and larger, rapid-growing fish found in alkaline waters derived from lime-bearing rocks. Results do not support the view that the small, slow-growing trout of acid waters are stunted owing to a food shortage.

96. Frost, W. E. 1940. Rainbows in acid water. A note on the trout of a peat lough on Arranmore. Salm. Trout Mag. 100: 234-240.

Lough Shure had a pH of 4.8 and contained a large population of rainbow trout. The growth and food of these rainbow trout are discussed.

97. Gardner, G. R., and P. P. Yevich. 1969. Toxicological effects of cadmium on Fundulus heteroclitus under various pH, oxygen, salinity and temperature regimes. Am. Zool. 9: 1096.

Incidence of kidney or intestinal lesions in mummichogs when exposed to cadmium were least under conditions of low pH.

98. Gjedrem, T. 1976. Genetic variation in tolerance of brown trout to acid water. SNSF-project, Norway, FR5/76, 11 p.

Differences between strains and families in egg and alevin mortality were highly significant and the estimated heritability of death rate in eyed-eggs was from 0.09-0.27. These results show that tolerance to acidic water is a heritable trait and that selection for higher survival rate in acidic water is promising.

99. Gjedrem, T. 1980. Genetic variation in acid tolerance in brown trout. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

A large improvement in survival rate of brown trout in acidic water may be obtained through selective breeding and crossbreeding.

100. Gjedrem, T. 1980. Growth and survival of fingerlings in acidic water. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Rainbow trout, Arctic char and brown trout were kept 4 mo in water of pH 6.2 and 5.5 and had similar growth curves. Rainbow trout and Arctic char kept at pH 4.8 had an 8% lower growth rate than fish kept at pH 6.2.

101. Goodnight, C. J. 1942. Toxicity of sodium pentachlorophenate and pentachlorophenol to fish. Ind. Eng. Chem. 34: 868-872.

A decrease in pH resulted in an increase in the toxicity of sodium pentachlorophenate and pentachlorophenol to fish.

102. Gorham, E. 1976. Acid precipitation and its influence upon aquatic ecosystems - an overview. Water Air Soil Pollut. 6: 457-481.

A review article.

103. Grahn, O. 1980. Fish kills due to high aluminum concentrations in lake water. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Fish kills in lakes and rivers of Sweden are not only caused by low pH values but more likely by a combination of high metal content and low pH. Aluminum concentration of 0.2 mg/L in waters with a pH of about 5.0 is very toxic for salmon.

104. Grahn, O., H. Hultberg, and L. Lander. 1974. Oligotrophication - a self-accelerating process in lakes subjected to excessive supply of acid substances. Ambio 3: 93-94.

All trophic levels in six lakes with pH values between 4.4 and 5.4 were investigated. It is suggested that the primary biological effects on individuals and populations of a continuous supply of acid substances to a lake induce profound, long-term changes, forcing the lake into an increasingly more oligotrophic state. This general oligotrophication of lakes tends - by means of a feedback mechanism - to further accelerate the process of acidification.

105. Grande, M. 1966. Vannets pH og dens betydning for ferskvannsfiske. En orietering om norske undersøkelsen og erfaringer. NIVA 0-139/64, 13 p. *

Summary of Norwegian information on the effect of acid waters on fish.

106. Grande, M., I. P. Muniz, and S. Andersen. 1979. The relative tolerance of some salmonids to acid waters. Verb. Internat. Verein. Limnol. 20: 2076-2084.

Salmonids can be ranked in the order brook trout, brown trout, Atlantic salmon, and rainbow trout, with brook trout as the most tolerant to low pH.

107. Gregory, L. 1974. The effect of effluent components from chlor-alkali plants on aquatic organisms: a literature review. Fish. Res. Board Can. Tech. Rep. 228, 94 p.

This review includes some coverage concerning the effects of pH on fish.

108. Grodziński, Z. 1970. The heart rate of sea-trout Salmo trutta L. embryos in Tyrode fluid at various pH. Acta Biol. Cracov. 13: 59-63.

The isolated hearts of freshly hatched sea trout embryos were kept for 1 h in Tyrode fluid at pH varying from 5.0-9.6. The acid solutions depressed the heart rate, or blocked the contractions of the ventricle and even the auricle. The more alkaline solutions diminished the number of contractions. These processes appeared to be reversible when the hearts were transferred into the basic fluid.

109. Grøterud, O. 1972. Zooplankton and fish in relation to acid melt water and anaerobic deep water in a lake. Vatten 28: 329-332. *

The distribution of fish in an acid lake near Oslo appears to be controlled by the pH in the surface waters and H_2S content of the hypolimnetic waters.

110. Grøterud, O. 1973. Noen sure innsjøer i Norge. Vatten 2: 153-158. *

Eight small lakes west of Oslo have low pH, low conductivity and declining fish populations.

111. Gunn, J. M. 1980. Effects of acid precipitation on fish stocks and amelioration efforts, in lakes near Sudbury, Ont. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

The status of fish communities in a large number of lakes near the metal smelting complex at Sudbury, Ontario, are discussed. Depressed pH and elevated metal levels combine to reduce game fish stocks.

112. Gutsell, J. S. 1929. Influence of certain water conditions, especially dissolved gases, on trout. Ecology 10: 77-96.

It was concluded that trout are tolerant to a considerable variation in pH; however, no limits in pH variation are given.

113. Hagen, A., and A. Langeland. 1973. Polluted snow in southern Norway and the effect of melt-water on freshwater and aquatic organisms. Environ. Pollut. 5: 45-57.

Analyses of snow, ice-trapped and surface water showed that polluted snow had a considerable influence on the quality of water in lakes and brooks in the winter and spring. The contaminants probably have had a negative effect on fish and invertebrates.

114. Hagen, O., and G. Norby. 1967. Noen undersøkelser i forbindelse med problemet surt vann og dets betydning for lakse - og ørretbestanden på Sørlandet. Norg. Jeg. og Fiskeforb. Tidsskr. 250-255. *

Salmon catch data from 1951-64 from several rivers in southern Norway are discussed on the basis of ambient pH resulting from acid precipitation.

115. Hall, A. R. 1925. Effects of oxygen and carbon dioxide on the development of the whitefish. Ecology 6: 104-116.

Whitefish eggs were incubated at pH 6.4, 7.0 and 8.0-9.0. Hydrogen ion concentrations favorable for fertilization are too high for later development. Optimum hydrogen ion concentration is gradually lowered as the embryo becomes older. Larvae reared in either acid or alkaline water high in bicarbonates both preferred alkaline water over acid water. When CO_2 was added to acid water of pH 6.3, mortality occurred. When H_2SO_4 was used to lower pH to 6.3, no mortalities occurred.

116. Hara, T. J. 1976. Effects of pH on the olfactory responses to amino acids in rainbow trout, Salmo gairdneri. Comp. Biochem. Physiol. 54A: 37-39.

Effects of pH on the olfactory responses to amino acids were studied electrophysiologically in rainbow trout. The responses to amino acids were highly pH dependent; responses were inhibited below pH 3.0 and above pH 10.0 The pH-response curve was specific for each amino acid tested; highly stimulatory amino acids had their maximal activity near their isoelectric points.

117. Hara, T. J., and S. MacDonald. 1976. Olfactory responses to skin mucous substances in rainbow trout Salmo gairdneri. Comp. Biochem. Physiol. 54A: 41-44.

The olfactory response of rainbow trout to skin mucous substances was pH dependent; the response-pH curve resembled curves obtained with free amino acids.

118. Harriman, R., and B. Morrison. 1980. Ecology of acid streams draining forested and non-forested catchments in Scotland. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Intense cultivation of conifers in Scotland has resulted in higher acidification of the forested streams as well as higher concentrations of aluminum and manganese. Furthermore, these streams have decreased fish population, and brown trout are absent in many.

119. Harrison, A. D. 1958. The effects of sulphuric acid pollution on the biology of streams in the Transvaal, South Africa. Verh. Internat. Verein. Limnol. 13: 603-610.

Gold and coal mining activities in the Transvaal, South Africa produce effluents or drainage waters with a pH as low as 2.3. No fish were found in highly acidic waters.

120. Hargis, J. R. 1976. Ventilation and metabolic rate of young rainbow trout (Salmo gairdneri) exposed to sublethal environmental pH. J. Exp. Zool. 196: 39-44.

Ventilation rate increased to either side of neutrality, but significantly fewer reversals, or "coughs," were observed at pH 6 and a greater number at pH 9 than occurred at pH 7 and 8 or in untested fish. The respiratory cough is shown to be pH dependent in rainbow trout and may therefore not be a reliable indicator of other pollution-caused stresses.

121. Harvey, H. H. 1975. Fish populations in a large group of acid-stressed lakes. Verh. Internat. Verein. Limnol. 19: 2406-2417.

The number of fish species was strongly correlated with lake pH. Also, the number of fish species was correlated significantly with the distance from the nearest and largest smelter in the La Cloche lakes area.

122. Harvey, H. H. 1979. The acid deposition problem and emerging research needs in the toxicology of fishes. Proc. Fifth Ann. Aquatic Toxicity Workshop, Hamilton, Ontario, Nov. 7-9, 1978. Fish. Mar. Serv. Tech. Rep. 862: 115-128.

The deposition of air-borne acid is causing the acidification of susceptible lakes and rivers in south-central Ontario. Fish populations respond with altered growth, failed recruitment of age classes, loss of older animals, and drastic reduction in abundance. The acid stress may lead to loss of populations, loss of entire species and even the extinction of fishes from such waters.

123. Harvey, H. H. 1980. Continuing changes in the fish fauna of the La Cloche mountain lakes. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Coincident with the increase in the hydrogen ion of these lakes, there has been a loss of fish species, changes in their abundance and growth, and failure of their maturation and their recruitment.

124. Harvey, H. W. 1927. Fundamental problems relating to river pollution. Nature, Lond. 119: 463-464.

The author reported that some observers found fish in waters of pH 4.4 but that was probably an extreme case. He suggests that the flora and fauna of a river probably would not be affected until the pH had decreased to about 5.5.

125. Hasler, A. D., O. M. Brynildson, and W. T. Helm. 1951. Improving conditions for fish in brown-water bog lakes by alkalization. J. Wildl. Mgt. 15: 347-352.

Alkalization of an acid brown water Wisconsin lake with lime resulted in a two-fold increase in transparency of the water in addition to an increase in oxygen levels at cooler strata. The resulting clearer water makes possible the capture of more energy, therefore increasing general lake productivity. The production of fish can thus be raised by increasing the volume of trophogenic zone.

126. Haupt, H. 1932. Fischsterben durch saures Wasser. Vom Wasser. 6: 261-262.

The author recounts a change in ground water level in which lowering brought dissolved oxygen into contact with mineral iron sulphide, caused formation of $FeSO_4$ which upon contact with air broke up into iron oxide and sulphuric acid. This water was brought to a pond containing carp during an increase in spring flow caused by a rise of ground water level, and had a pH of about 4.5. The fish died within 5 d.

127. Hayes, F. R. 1942. The hatching mechanism of salmon eggs. J. Exp. Zool. 89: 357-373.

The ambient pH of maximum hatching enzyme action was pH 9.6 which was peculiar because the pH of the perivitelline fluid was 4.8. However, it was considered that the surface of the embryonic and yolk ectoderm was alkaline and this, in contact with the inside of the capsule, made it possible for the enzyme to act in nature.

128. Hendry, G. R., K. Baalsrud, T. S. Traaen, M. Laake, and G. Raddum. 1976. Acid precipitation: Some hydrobiological changes. Ambio 5: 224-227.

Acid precipitation in southern Norway has resulted in lakes declining in their pH values accompanied by the disappearance of fish, especially salmonids. More subtle changes in fish populations may result indirectly from acid-induced changes in food supply organisms at levels pH 5.0-6.0.

129. Hendrey, G. R., and R. F. Wright. 1976. Acid precipitation in Norway: Effects on aquatic fauna. J. Great Lakes Res. 2(suppl. 1): 192-207.

A review paper.

130. Henrikson, L., B. I. Nilsson, H. G. Nyman, H. G. Oscarson, and J. A. E. Stenson. 1980. Changes in predator-prey relations important for the development in acidified lakes. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

The disappearance of fish in acidified lakes has led to a rapid increase in abundance of a number of species susceptible to fish predation. The vertebrate predator system has hence been replaced by an invertebrate predator system whose far-reaching influences are discussed.

131. Herrmann, R., and J. Baron. 1980. Aluminum mobilization in acid environments Great Smoky Mountains National Park. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Acid runoff as low as pH 4.1 in perennial mountain streams was characterized by visible aluminum hydroxide precipitates on stream substrates. Brook trout populations were adversely affected for 13 km downstream from an acid source. Gill hyperplasia was observed in brook trout of these waters.

132. Hodson, P. V., B. R. Blunt, and D. J. Spry. 1978. pH-induced changes in blood lead of lead-exposed rainbow trout (Salmo gairdneri). J. Fish. Res. Board Can. 35: 437-445.

Toxicity of lead to juvenile rainbow trout increases as pH decreases. Experimental pH ranged from 10.0 to 6.0.

133. Hoehn, R. C., and D. R. Sizemore. 1977. Acid mine drainage (AMD) and its impact on a small Virginia stream. Water Resources Bull. 13: 153-160.

Active pyrite (FeS_2) mining in Chestnut Creek in Virginia resulted in an absence of fish, possibly because of the lack of food, the unsuitability of bottom substrate for nesting and the probable irritating nature of the water with $Fe(OH)_3$ floc and dilute constituents of acid mine drainage.

134. Hogendoorn-Roozemond, A. S., V. J. H. M. Holder, J. J. T. W. A. Strik, Z. Kolar, and J. H. Koeman. 1978. The influence of the pH on the toxicity of hexavalent chromium to rainbow trout (Salmo gairdneri). In Aquatic pollutants: transformation and biological effects, O. Hutzinger, I. H. van Lelyveld, and B. C. J. Zoeteman (eds.). Pergamon Press, Oxford, U.K., p. 477-478.

The toxicity of chromates is pH dependent. A 50- 200-fold increase in toxicity was observed when the pH decreased from 7.9 to 6.8.

135. Höglund, L. B. 1961. The reactions of fish in concentration gradients. Rep. Inst. Freshw. Res., Drottningholm 43, 147 p.

All fish species studied were able to avoid adverse conditions in pH and combined pH/CO_2 gradients. Fish were able to detect and avoid CO_2 separately from the accompanying pH. Roaches show avoidance of lower pH than about 5.6 and Atlantic salmon parr to lower pH than about 5.3.

136. Höglund, L. B., and J. Härdig. 1969. Reactions of young salmonids to sudden changes of pH, carbon-dioxide tension and oxygen content. Rep. Inst. Freshw. Res., Drottningholm 49: 76-119.

Decreasing pH, combined with increased CO_2 tension provoked changes in locomotor behavior and ventilation among Atlantic salmon parr. Extremely adverse pH/pCO_2 conditions, in combination with low O_2 gave rise to delayed chromatophore reactions. Respiratory distress was also noted for both of the above conditions.

137. Höglund, L. B., and A. Persson. 1971. Effects of locomotor restraint and of anaesthesia with urethane or MS-222 on the reactions of young salmon (Salmo salar L.) to environmental fluctuations of pH and carbon dioxide tension. Rep. Inst. Freshw. Res., Drottningholm 51: 75-88.

Variations of the pH between 7.5 and 6.8 and of pCO_2 between about 5 and about 30 mm Hg gave reproducible ventilatory and locomotor reactions in second-summer parr of Salmo salar (L.). The technique described should be of value for checking the effect of toxic substances in waste water. By repeated CO_2-response tests, it might be possible to determine whether fish which have been exposed to certain environmental poisons in sublethal concentrations subsequently display transient reflex and behavioral disturbances or damage of a more permanent nature.

138. Holt-Jensen, A. 1973. Acid rains in Scandinavia. Ecologist 3: 378-382.

Effects of acid rain on the freshwater fisheries of Scandinavia are briefly reviewed.

139. Hopkins, E. S. 1928. The effect of slightly alkaline tap water upon spawn and eggs of trout and perch. J. Am. Water Works Assoc. 19: 313-322.

Reported fatalities of embryos and fry of trout and perch in slightly alkaline water after transference from water containing free CO_2.

140. Huckabee, J. W., C. P. Goodyear, and R. D. Jones. 1975. Acid rock in the Great Smokies: unanticipated impact on aquatic biota of road construction in regions of sulfide mineralization. Trans. Am. Fish. Soc. 104: 667-684.

Lowered pH and increased sulfate and metal concentrations derived from the leaching of sulfide-rich rocks were responsible for trout mortalities. The small stream draining this area of roadbed fill remained devoid of fish for 8 km downstream after 10 yr. The downstream water had a pH of 4.5-5.9; upstream from the fill the pH was 6.5-7.0.

141. Huet, M. 1941. pH value and reserves of alkalinity. Commun. Sta. Rech. Groenendael 1: 24.

Fish in water with a low reserve of alkalinity may be killed by a sudden reduction in pH value. In general pH values below about 4.8 are toxic to fish; in the presence of large quantities of iron, fish may be killed by a pH value of 5.5.

142. Huet, M. 1941. Esquisse hydrobiologique des eaux piscicoles de la Haute-Belgique. Trav. Sta. Rech. Groenendael 2: 47.

Waters with a pH value below 4.8 are unsuitable for growth of fish in Upper Belgium. Trout grow more slowly in acid than in alkaline waters.

143. Huitfeldt-Kaas, H. 1922. Om aarsaken til massedød av laks og ørret i Frafjord-elven, Helle-elven og Dirdalselven i Ryfylke høsten 1920. Norges Jaeger. Fiskfor. Tidsskr. 51: 37-44. *

Autumn salmon kills of 1920 are ascribed to the washout of humic substances from the soils following an unusually dry summer.

144. Hultberg, H. 1977. Thermally stratified acid water in late winter - a key factor inducing

self oligotrophication processes which increase acidification. Water Air Soil Pollut. 7: 279-294.

Ion separation of acid air pollutants out of snow causes sudden, deep pH drops in lakes and running waters at an early stage of snow-melting. These pH drops have drastic effects on fish populations and are suggested to be the main cause of Sphagnum invasion and changes in the microflora already at an early stage of acidification, i.e. when summer pH values are about 6. These effects in turn reduce the nutrient recycling and accelerate the acidification process.

145. Inaba, D., M. Nomura, and M. Suyama. 1958. Studies on the improvement of artificial propagation in trout culture. II. On the pH values of eggs, milt, coelomic fluid and others. Bull. Jap. Soc. Scient. Fish. 23: 762-765.

The pH of adult trout coelomic fluid is 7.61-8.14. The pH value of the testis gradually increased from the anterior toward the posterior. Milt ranged pH 7.84-8.14 and averaged pH 8.03. Sperm move within the range of pH 4.5-10.4 and were more active in the basic pH range. Egg surfaces were pH 8.10-8.59 and averaged pH 8.27. The pH of the egg content was 6.53-6.68 and averaged pH 6.63.

146. Ishio, S. 1965. Behaviour of fish exposed to toxic substances. Adv. Water Pollut. Res. 1: 19-33.

Most fish are attracted into alkaline waters. The fathead minnow was allured into water of pH 8.5-9.0 but avoided water above pH 9.2.

147. Jacobsen, O. J. 1977. Brown trout (Salmo trutta L.) growth at reduced pH. Aquaculture 11: 81-84.

Growth of brown trout yearlings at levels of pH 6.26, 5.44 and 5.00 during a 48-d period were similar.

148. Janssen, R. G., and D. J. Randall. 1975. The effects of changes in pH and P_{CO_2} in blood and water on breathing in rainbow trout, Salmo gairdneri. Respir. Physiol. 25: 235-245.

A reduction in environmental pH caused a reduction in arterial pH but only a slow gradual increase in gill ventilation. Changes in pH in blood or water have little direct effect on gill ventilation in rainbow trout.

149. Jensen, K. W., and E. Snekvik. 1972. Low pH levels wipe out salmon and trout populations in southernmost Norway. Ambio 1: 223-225.

Low pH values have nearly eradicated the salmon populations in a number of rivers in the southernmost districts of Norway. Low pH values have, during the past 20-30 yr, eradicated populations of brown trout in a great number of lakes and rivers in the same districts, and this alarming development continues today.

150. Jewell, M. E. 1922. The fauna of an acid stream. Ecology 3: 22-28.

A river in Illinois varied from pH 5.8-7.2. Higher acidity levels occurred in winter. Fish fry and fingerlings were abundant during the summer in weakly acid water, pH 6.8.

151. Jewell, M. E., and H. Brown. 1924. The fishes of an acid lake. Trans. Am. Micro. Soc. 43: 77-84.

Vincent Lake, Michigan had a pH of 4.4 and contained four species of fish, Perca flavescens, Ameriurus nebulosis, Lepomis incisor and Esox lucius, but no molluscs.

152. Jobes, F. W., and M. E. Jewell. 1927. Studies on the alkali reserve of the blood of Ameriurus nebulosus from acid and basic waters. Trans. Am. Micro. Soc. 46: 175-186.

There was no correlation between the pH of the blood of fishes and the pH of the water in which they lived.

153. Johansen, K., G. M. O. Maloiy, and G. Lykkeboe. 1975. A fish in extreme alkalinity. Respir. Physiol. 24: 159-162.

Tilapia grahami, a small cichlid fish, inhabits extremely alkaline water where pH ranges between 9.6 and 10.5. Venous blood has blood pH 8.4. A 10- to 15-fold bicarbonate concentration gradient exists across the gills.

154. Johansson, N., and J. E. Kihlström. 1975. Pikes (Esox lucius L.) shown to be affected by low pH values during first weeks after hatching. Environ. Res. 9: 12-17.

Newly hatched pike sac fry were reared for 8 d at different pH levels. Mortalities were 17, 26, and 97% at levels pH 6.8, 5.0, and 4.2, respectively.

155. Johansson, N., J. E. Kihlström, and A. Wahlberg. 1973. Low pH values shown to affect developing fish eggs (Brachydanio rerio Ham. - Buch.). Ambio 2: 42-43.

Fish eggs hatching success decreases from about 50% at pH 7 to about 4% at pH 4, the young embryos being those most sensitive to the acid water. There is a tendency towards a prolongation of the period from fertilization to hatching at low pH values. In slightly alkaline solutions hatching success remains unchanged, but there is a slight shortening of the period from fertilization to hatching.

156. Johansson, N., and G. Milbrink. 1976. Some effects of acidified water on the early development of roach (Rutilus rutilus L.) and perch (Perca fluviatilis L.). Water Resour. Bull. 12: 39-48.

Eggs of perch and roach had at least a 50% decrease in hatching success when reared below pH 5.6. Both species illustrated an almost complete lack of reproduction below pH 4.6. Roach was more sensitive than perch to low pH.

157. Johansson, N., P. Runn, and G. Milbrink. 1977. Early development of three salmonid species in acidified water. Zoon 5: 127-132.

Eggs of sea-run brown trout, Atlantic salmon, and brook trout were reared in acid waters until just prior to resorption of the yolk of the fry. Salmon were the most pH-sensitive species. An increase in mortality could be discerned at pH 5.0. Brown trout and brook trout were less pH-sensitive. Both species showed a lower limit of tolerance slightly below pH 5.0. Brook trout gave few signs of being affected until about pH 4.5.

158. Johnson, D. W. 1968. Pesticides and fishes - a review of selected literature. Trans. Am. Fish. Soc. 97: 398-424.

This paper includes a brief discussion of the effects of ambient pH and pesticides on fish.

159. Johnson, D. W., and D. A. Webster. 1977. Avoidance of low pH in selection of spawning sites by brook trout (Salvelinus fontinalis). J. Fish. Res. Board Can. 34: 2215-2218.

Female brook trout avoided upwellings of pH 4.0 and 4.5 in preference to those of pH 6.7 or 8.0. Discrimination was not evident at pH 5.0. Test levels included pH 8.0, 6.7, 5.0, 4.5, and 4.0.

160. Jonas, R. E. E., H. S. Sehdev, and N. Tomlinson. 1962. Blood pH and mortality in rainbow trout (Salmo gairdneri) and sockeye salmon (Oncorhynchus nerka). J. Fish. Res. Board Can. 19: 619-624.

Rainbow trout died when their blood pH was lowered into the range of 6.8-6.9 by injection of either hydrochloric acid or lactic acid.

161. Jones, J. R. E. 1939. The relation between the electrolytic solution pressures of the metals and their toxicity to the stickleback (Gasterosteus aculeatus L.). J. Exp. Biol. 16: 425-437.

Lethal concentration limits have been determined for hydrogen ion and ions of 18 metals on the three-spined stickleback. According to their lethal concentration limits on a mg/L basis, their order of increasing toxicity is Sr, Ca, Na, Ba, Mg, K, Mn, Co, Cr, Ni, Au, Zn, Cd, Pb, Al, Cu, H, Hg, Ag. All of these ions, with the exception of the first six (the metals of alkalis and alkaline earths), bring about the death of fish by precipitating on the gills. The alkali and alkaline earth metals appear to enter the body and act as true internal poisons.

The toxicity of solutions of iron salts appears to be due, mainly if not entirely, to their acidity.

162. Jones, J. R. E. 1948. A further study of the reactions of fish to toxic solutions. J. Exp. Biol. 25: 22-34.

Threespine stickleback will avoid water more acid than pH 5.6 or more alkaline than pH 11.4. Over the range pH 5.8-11.2 the fish are indifferent or very slightly attracted.

163. Jones, J. R. E. 1962. Fish and river pollution, p. 254-310. In River Pollution II Causes and Effects, L. Klein (ed.). Butterworths, London.

This article includes discussion of the effects of ambient pH on fish.

164. Jones, J. R. E. 1964. Fish and River Pollution, p. 107-117. Butterworths, London.

A review of acid and alkalies and pH tolerance limits of fish.

165. Jordan, D. H. M., and R. Lloyd. 1964. The resistance of rainbow trout (Salmo gairdneri Richardson) and roach (Rutilus rutilus (L.)) to alkaline solutions. Int. J. Air Water Pollut. 8: 405-409.

A 15-d LL50 to alkaline pH of 9.5 for rainbow trout was determined. A 10-d LL50 to alkaline pH of 10.15 for roach was also determined. Results indicate that rainbow trout might be harmed if exposed to pH values of 9.0 or above for several months.

166. Jozuka, K., and H. Adachi. 1979. Environmental physiology on the pH tolerance of the teleost. 2. Blood properties of medaka, Oryzias latipes, exposed to low pH environment. Annot. Zool. Jap. 52: 107-113.

Medaka exposed to pH 4.0 for 4 h had a blood pH decrease from 7.34 to 6.99 and plasma Na concentration markedly decreased. When large Ca^{++} concentrations were present, Na^{+} did not decrease.

167. Katz, M. 1971. The effects of pollution upon aquatic life, p. 297-328. In Water and Water Pollution Handbook, Vol. 1, L. L. Ciaccio (ed.). Marcel Dekker, Inc., New York.

This review includes some mention of pH effects on fish.

168. Katz, M., and R. T. Oglesby. 1967. A review of the literature of 1966 on wastewater and water pollution control. Biology. J. Water Pollut. Cont. Fed. 39: 1049-1096.

A review containing a few comments on the effects of pH on fish.

169. Katz, M., D. E. Sjolseth, D. R. Andersson, and L. R. Tyner. 1970. A review of the 1969 literature on wastewater and water pollution. Effects of pollution on fish life. J. Water Pollut. Cont. Fed. 42: 983-1002.

A review containing a few comments on the effects of pH on fish.

170. Kemp, H. T., J. P. Abrams, and R. C. Overbeck. 1971. Effect of chemicals on aquatic life. Water Quality Criteria Data Book, 3, 528 p.

A review containing some effects of pH on fish.

171. Kimmel, W. G., and W. E. Sharpe. 1975. Acid drainage and the stream environment. Trout Mag. 21-25.

Acid mine drainage has rendered 5000 mi of streams in Appalachia unsuitable for fishes. Reclamation is discussed.

172. Kinne, O., and H. Rosenthal. 1967. Effects of sulfuric water pollutants on fertilization, embryonic development and larvae of the herring *Clupea harengus*. Mar. Biol. 1: 65-83.

Sulfuric pollutants (largely $FeSO_4$ and H_2SO_4) released at sea affect herring at dilutions as low as 1:32,000. Reductions were reported for success of fertilization, egg survival, embryonal growth rate, incubation period, percentage of successful hatch. Increases were noted for heart frequency and structural abnormalities of freshly hatched larvae. Impaired locomotor response was observed. Death occurred at dilutions of 1:8000.

173. Kinney, E. C. 1964. Extent of acid mine pollution in the United States affecting fish and wildlife. U.S. Bur. Sport Fish. Wildl. Circ. 191, 27 p.

Acid mine pollution has destroyed fish habitats in 5,890 mi of streams in the U.S.

174. Kjos-Hanssen, B. 1970. Fiske og surt vann. Fiskedodeligheten har virkelig skutt fart i 1950/60-årene. Tekn. Ukebl. 117: 38.

Fish populations have been affected adversely during the 1950's and 1960's by acid precipitation.

175. Klarberg, D. P., and A. Bensen. 1975. Food habits of *Ictalurus nebulosus* in acid polluted water of northern West Virginia. Trans. Am. Fish. Soc. 104: 541-547.

No qualitative difference in food habits was noted between different size groups of fish in either acid or non-acid situations.

176. Klein, L. 1957. Aspects of River Pollution. Butterworths, London.

This text includes discussion on the effects of pH on fish.

177. Klein, L. 1962. River Pollution. II. Causes and Effects. Butterworths, London.

This text includes discussion of the effects of pH on fish.

178. Krishna, D. 1953. Effect of changing pH on developing trout eggs and larvae. Nature 171: 434.

The pH value of yolk in living trout eggs is 6.50-6.55, and after death it has the same pH as that of the surrounding water. In alkaline medium, there was endosmosis and metabolic activity appeared to slow down. In acidic medium, exosmosis existed and metabolic activity appeared to accelerate.

179. Kwain, W. 1975. Effects of temperature on development and survival of rainbow trout, *Salmo gairdneri*, in acid waters. J. Fish. Res. Board Can. 32: 493-497.

Differences in mortality of rainbow trout embryos were significant when the eggs were exposed to 5, 10, and 15°C and pH levels from 3.0-6.0. No embryos survived at pH values below 4.49, regardless of the temperature. The median lethal pH values for rainbow embryos were 4.75 and 5.52 at temperatures of 10 and 5°C, respectively.

Differences in lethal pH values for fingerling rainbow trout were significant when trout were exposed to four test water temperatures (5, 10, 15, and 20°C) and two acclimation temperatures (10 and 20°C). The median lethal pH values of fingerling trout were positively related to the test water temperatures and ranged from 3.86-4.49. Resistance of yearling trout to acid waters was higher than that of fingerlings.

180. Labat, R., J. K. Laffont, and A. Cadastraing. 1969. Le pH du milieu ambiant et ses effets sur l'électrocardiogramme de quelques téléosteens dulçaquicoles. Part 1. Bull. Soc. Hist. Nat. Toulouse 105: 167-180.

Alkaline waters increased the wave amplitude of fish ECG while acid waters had a reverse reaction. Bradycardia was observed in fish in alkaline waters, but tachycardia was observed in acid waters. At lethal levels of pH, carp produced copious amounts of mucus and were more resistant than perch which produced less mucus.

181. Labat, R., J. K. Laffont, A. Cadastraing, and L. Bonnet. 1969. Le pH du milieu ambiant et ses effets sur l'électrocardiogramme de quelques téléosteens dulçaquicoles. Part 2. Bull. Soc. Hist. Nat. Toulouse 105: 455-463.

A relationship between blood pH (y) of a teleost and ambient pH (x) may be stated as $y = ax + b$; where the square root of the ECG amplitude and the water temperature are known.

182. Laurent, P. 1969. Action du pH et de la P_{O_2} sur le potential de membrane des cellules de l'épithélium récepteur dans la pseudobranchie d'un poisson Téléostéen. Rev. Can. Biol. 28: 149-155.

In the epithelium of the teleost pseudobranch membrane potentials change reversibly with P_{O_2} and pH shifts. Each pair of physiological P_{O_2} and pH values sets up a defined membrane potential.

183. Leivestad, H., G. Hendrey, I. P. Muniz, and E. Snekvik. 1976. Effects of acid precipitation on freshwater organisms, p. 87-111. *In* Impact of acid precipitation on forest and freshwater ecosystems in Norway, F. H. Braekke (ed.). SNSF Project, Norway FR 6/76.

In Norway, fish populations are severely affected by the increased acidity of fresh waters from acid precipitation. Salmon has

been eliminated from major rivers and the disappearance of trout populations from hundreds of lakes has been rapid over the last decades. Physiological studies indicate that failure in body salt regulation is the primary cause of fish death in acid water. Also, trout disappear at a higher pH in lakes of extremely low ion content.

184. Leivestad, H., and I. P. Muniz. 1974. Fiskedøk ved lav pH. SNSF-Project, Norway, TN 4/74, 17 p.

Blood of acid stressed fish have abnormal levels of Na^+, Cl^-, pH and HCO_3^-.

185. Leivestad, H., and I. P. Muniz. 1976. Fish kill at low pH in a Norwegian river. Nature 359: 391-392.

A massive fish kill in the Tovdal River in southern Norway in 1975 during early phase of snow melting has been attributed to an impairment of the active transport mechanism for sodium and/or chloride ions through the gill epithelium of the fish due to acid waters. The plasma content of potassium, calcium and magnesium was not affected by low pH.

186. Leivestad, H., and I. P. Muniz. 1980. Acid stress in trout from a dilute mountain stream. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Fish disappear at higher pH in lakes with extremely low ion content.

187. Leivestad, H., I. P. Muniz, K. Fugelli, T. Vislie, and B. O. Rosseland. 1980. Physiological responses to acid stress in fish. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

This review includes effects of low pH on the ionic regulation, ventilation, oxygen uptake, acid-base balance and on the direct effects on the exchange mechanisms and secondary effects at the tissue level.

188. Lewis, W. M., and C. Peters. 1956. Coal mine slag drainage. Industr. Wastes 1: 145-147.

Slag drainage accumulates in ditches and puddles and is then flushed into streams in large quantities by heavy rains killing fish. The lethal effect of slag drainage results from the free acid which it contains. A pH value as low as 3.5 causes fish mortality in a short time. A pH value of 4.0-4.5 causes pronounced gill irritation.

189. Likens, G. E. 1976. Acid precipitation. Chem. Eng. News 54: 29-44.

General survey on acid precipitation and associated phenomena including declining fish populations.

190. Likens, G. E., R. F. Wright, J. N. Galloway, and T. J. Butler. 1979. Acid rain. Sci. Am. 241: 43-51.

A general review of acid rain.

191. Lipschuetz, M., and A. L. Cooper. 1961. Toxicity of 2-secondary-butyl-4,6-dinitrophenol to blacknose dace and rainbow trout. N.Y. Fish Game J. 8: 110-121.

This herbicide is more toxic by five-fold at pH 6.9 than at pH 8.0 for rainbow trout.

192. Lloyd, R. 1960. The toxicity of zinc sulphate to rainbow trout. Ann. Appl. Biol. 48: 84-94.

Zinc sulphate was less toxic to rainbow trout in hard water (pH 7.8) than in soft water (pH 6.5). The cause of death of fish in solutions of zinc sulphate was not by the precipitation of mucus on the gills but probably by damage to the gill epithelium.

193. Lloyd, R., and D. W. M. Herbert. 1960. The influence of carbon dioxide on the toxicity of unionized ammonia to rainbow trout (Salmo garidneri Richardson). Ann. Appl. Biol. 48: 399-404.

Quantitative measurements for the relationship between the concentration of free CO_2 in water and the toxicity of unionized ammonia are correlated with a theoretical estimation of pH value of water at the gill surface.

194. Lloyd, R., and D. H. M. Jordan. 1964. Some factors affecting the resistance of rainbow trout (Salmo gairdneri Richardson) to acid waters. Int. J. Air Water Pollut. 8: 393-403.

Results suggest that exposure to pH values below 5.0 for about 3 mo might be harmful to rainbow trout when little free carbon dioxide was present in the water, but if an acid discharge were to raise the free carbon dioxide content to 20 ppm, mortalities might occur within 3 mo when the pH value of the water fell below 6.0. Comparisons of the pH value and total carbon dioxide content of the blood of rainbow trout killed in acid solutions with those of control fish suggested that death was due to acidaemia.

195. Lockhart, W. L., and A. Lutz. 1977. Preliminary biochemical observations of fishes inhabiting an acidified lake in Ontario, Canada. Int. J. Water Air Soil Pollut. 7: 317-332.

Results indicate that potential mechanisms of fish losses such as asphyxia and starvation are unlikely to occur in acid lakes. They suggest Ca^{++} dynamics may limit ovarian development and that absorption of this metal at exchange surfaces may be impaired.

196. Longwell, J., and F. T. K. Pentelow. 1935. The effect of sewage on brown trout (Salmo trutta L.). J. Exp. Biol. 12: 1-12.

There was no variation in toxicity of sodium sulphide to trout between pH values of 6.9 and 7.6. At high pH values the sodium sulphide solution was much less toxic than at low values. This suggests that the toxicity is increased by the formation of free hydrogen sulphide.

197. Maetz, J. 1972. Interaction of salt and ammonia transport in aquatic organisms, p. 105-154. In Nitrogen Metabolism and the

Environment, J. W. Campbell and L. Goldstein (eds.). Academic Press, London and New York.

A sudden drop in ambient pH results in significant permeability alterations of the goldfish gill epithelium. Na^+ transport is inhibited at low pH.

198. Maetz, J. 1973. Na^+/NH_4^+, Na^+/H^+ exchanges and NH_3 movement across the gill of Carassius auratus. J. Exp. Biol. 58: 255-275.

A decrease of the external pH by one unit results in a 50-60% decrease in both influx and efflux of sodium. A transient augmentation of the rate of ammonia excretion is observed upon acidification, suggesting an increased permeability of the gill to the free-base form of ammonia.

199. Mahdi, M. A. 1973. Studies on factors affecting survival of Nile fish in Sudan. 1. The effect of hydrogen ion concentration. Mar. Biol. 18: 89-92.

Young Tilapia died in test waters of pH 2.9, but survived waters of pH 3.5 for 24 h.

200. Marking, L. L. 1975. Effects of pH on toxicity of antimycin to fish. J. Fish. Res. Board Can. 32: 769-773.

Antimycin is biologically unavailable at high pH. Toxicity of antimycin decreased gradually from pH 6.5-8.5 and abruptly from 8.5-9.5 with carp, green sunfish, and bluegill. Water hardness had little or no effect on toxicity.

201. Marking, L. L., and J. W. Hogan. 1967. Toxicity of Bayer 73 to fish. In Investigations in Fish Control, No. 19. U.S. Fish Wildl. Serv. Bur. Sport Fish. Wildl. Resour. Publ. 36, 13 p.

Bayer 73, a molluscicide, is highly toxic to a variety of freshwater fish. Goldfish were tested at pH 5, 7, and 10. There was no change in toxicity between pH 6.4-8.0. Extreme pH levels significantly reduce the toxicity of Bayer 73 to fish.

202. Marking, L. L., and C. R. Walker. 1973. The use of fish bioassays to determine the rate of deactivation of pesticides, p. 357-366. In Bioassay Techniques and Environmental Chemistry. Ann Arbor Sci. Publ. Inc.

The half-life of biological activity of antimycin, a powerful fish toxicant, was determined for rainbow trout, goldfish, channel catfish, black bullhead, green sunfish, and bluegill. Antimycin was deactivated rapidly in high pH waters.

203. Mawdesley-Thomas, L. E., and D. W. Jolly. 1967. Diseases of fish - II. The goldfish (Carassius auratus). J. Small Anim. Pract. 8: 533-541.

In some cases, where practical, transient manipulations in the temperature, pH or especially salinity of water can alleviate the disease, either by a direct action on the pathogenic organism or indirectly by killing the free-living infective agent.

204. McCarraher, D. B. 1962. Northern pike, Esox lucius, in alkaline lakes of Nebraska. Trans. Am. Fish. Soc. 91: 326-329.

The northern pike has survived in Nebraska waters having average pH values of 9.5. In Nebraska, 48% of the pike habitat exceeds the 9.0 pH level. Fry appear to be more sensitive to extremes of pH than adults.

205. McCarraher, D. B. 1971. Survival of some freshwater fishes in the alkaline eutrophic waters of Nebraska. J. Fish. Res. Board Can. 28: 1811-1814.

Total alkalinities, pH and other water chemistry parameters are given for 13 alkaline lakes where pH ranged from 8.5-10.5. Some of 14 freshwater fish species were tested in one or more lakes. Centrachid fishes were generally more sensitive and perch, fathead minnow, northern pike, and black bullhead were most tolerant.

206. McCarraher, D. B., and R. Thomas. 1968. Some ecological observations on the fathead minnow, Pimephales promelas, in the alkaline waters of Nebraska. Trans. Am. Fish. Soc. 97: 52-55.

Lakes with levels pH 8.8-9.5 support populations of fathead minnows.

207. McKee, J. E., and H. W. Wolf. 1963. Water Quality Criteria, 2nd Edition. Calif. State Water Resource Control Board Publ. A-3, 548 p.

This report includes discussions on the effects of pH on fish and recommends water quality criteria for pH.

208. McKenna, M. G., and F. Duerr. 1976. Effects of ambient pH on the gills of Ictalurus melas Raf. Am. Zool. 16: 224.

Gills of black bullheads exposed to acid and alkali waters had different types of edema occurring between the outer lamellar cells and the remaining gill tissue. Increased alkali led to more pounounced edema and breakage in cell layer. Lamellae of acid fish became eroded and filament swollen.

209. McKim, J. M., R. L. Anderson, D. A. Benoit, R. L. Spehar, and G. N. Stokes. 1976. Effects of pollution on freshwater fish. J. Water Pollut. Cont. Fed. 48: 1544-1620.

This paper includes the year's review of pH effects on fish.

210. McKim, J. M., D. A. Benoit, K. E. Biesinger, W. A. Brungs, and R. E. Siefert. 1975. Effects of pollution on freshwater fish. J. Water Pollut. Cont. Fed. 47: 1711-1768.

This paper includes the year's review of pH effects on fish.

211. McKim, J. M., G. M. Christensen, J. H. Tucker, D. A. Benoit, and M. J. Lewis. 1973. Effects of pollution on freshwater fish. J. Water Pollut. Cont. Fed. 45: 1370-1407.

This paper includes the year's review of the effects of pH on fish.

212. McKim, J. M., G. M. Christensen, J. H. Tucker, D. A. Benoit, and M. J. Lewis. 1974. Effects of pollution on freshwater fish. J. Water Pollut. Cont. Fed. 46: 1540-1591.

A literature review of research for 1973.

213. McWilliams, P. G., D. J. A.Brown, G. D. Howells, and W. T. W. Potts. 1980. Physiology of fish in acid waters. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Physiological data can be used to predict the survival of fish to sudden or progressive pH changes in natural waters, and to assess the consequences of remedial measures.

214. McWilliams, P. G., and W. T. W. Potts. 1978. The effects of pH and calcium concentrations on gill potentials in the brown trout, Salmo trutta. J. Comp. Physiol. 126: 277-286.

The transepithelial potential across the gills of brown trout was strongly dependent on external pH, being negative in neutral solutions but positive in acid solutions. The addition of calcium to the external medium produced a positive shift in potential in all but the very acid media (pH 4.0-3.5). The gill membrane appears to act as a hydrogen electrode having a very high permeability to H^+ ions, and the potential behaves as a diffusion potential. The positive potential at low pH largely accounts for the increased loss of sodium from fish in these conditions.

215. Menendez, R. 1976. Chronic effects of reduced pH on brook trout (Salvelinus fontinalis). J. Fish. Res. Board Can. 33: 118-123.

During an 11-mo period all developmental stages of the brook trout were continuously exosed to pH levels of 4.5, 5.0, 5.5, 6.0, 6.5, and the control 7.1. The number of viable eggs was reduced significantly at pH 5.0 and to a lesser extent at the higher pH levels. Embryo hatchability was significantly less at all pH levels below 6.5. Growth and survival of alevins was reduced at the lower pH levels. These data indicate that continual exposure to pH values below 6.5 will result in significant reductions in egg hatchability and growth.

216. Menzies, W. J. M. 1927. River pollution and the acidity of natural waters. Nature, Lond. 119: 638-639.

Trout and salmon parr can survive in water of pH 4.5-6.0.

217. Merlini, M., and G. Pozzi. 1977. Lead and freshwater fishes: Part I. Lead accumulation and water pH. Environ. Pollut. 12: 167-172.

The accumulation of lead by an edible freshwater fish was investigated at pH 7.5 and pH 6.0. At the lower pH the fish concentrated almost three times more lead than at the higher pH. The sites of lead accumulation, however, were not altered by the change in water pH.

218. Milbrink, G., and N. Johansson. 1975. Some effects of acidification on roe of roach, Rutilus rutilus L., and perch, Perca fluviatilis L. - with special reference to the Åvaå Lake system in eastern Sweden. Rep. Inst. Freshw. Res. Drottningholm 54: 52-62.

LL50 for pH for roe of roach and perch was pH 5.5 and 4.7, respectively for both in situ and in vitro. Fish may get acclimatized to acid conditions when exposed for a long time.

219. Mount, D. I. 1966. The effect of total hardness and pH on acute toxicity of zinc to fish. Int. J. Air Water Pollut. 10: 49-56.

At any given hardness, zinc was always more toxic to minnows at a high pH than at a low pH. Levels of pH were 6, 7, and 8.

220. Mount, D. I. 1973. Chronic effect of low pH on fathead minnow survival, growth and reproduction. Water Res. 7: 987-993.

Fathead minnows survived levels as low as pH 4.5. Fish behavior was abnormal, and fish were deformed at levels pH 4.5 and 5.2 after 13 mo exposure. A pH of 6.6 was marginal for vital life functions. The fish did not become acclimated to low levels of pH.

221. Mudge, J. E., J. L. Dively, W. H. Neff, and A. Anthony. 1977. Interrenal histochemistry of acid-exposed brook trout, Salvelinus fontinalis (Mitchill). Gen. Comp. Endocrinol. 31: 208-215.

Acute exposure of brook trout to waters of low pH resulted in a marked inhibition of RNA synthesis and presumably of steroidogenesis in the interrenal tissue.

222. Muniz, I. P., and H. Leivestad. 1980. Toxic effects of aluminium on the brown trout, Salmo trutta. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

At pH 4.0 and 6.0 no effects of aluminium addition to brown trout were found and maximum toxicity seems to be at pH 5.0. The toxic action of aluminium seems to be a combined effect of impaired ion exchange and respiratory distress caused by mucus clogging of the gills.

223. Murdock, H. R. 1953. Industrial wastes: Some data on toxicity of metals in wastes to fish life are presented. Industr. Eng. Chem. 45: 99A-100A, 102A.

Summarizes toxicity data of alkalies, acids, and salts given by Doudoroff and Katz (1950).

224. National Technical Advisory Committee. 1968. Water Quality Criteria. U.S. Fed. Water Pollut. Cont. Admin., Wash. D.C., 234 p.

This report includes pH criteria as determined for various bodies of water and includes discussion on the effects of pH on fish.

225. Neess, J. C. 1949. Development and status of pond fertilization in central Europe. Trans. Am. Fish. Soc. 76: 335-358.

Weakly alkaline waters of pH 7-8 are most productive in fish ponds and very acid waters are distinctly undesirable for fish culture. At pH 5.5, fish develop hypersensitivity to bacterial parasites and generally do not survive waters below pH 4.5.

226. Neville, C. M. 1979. Sublethal effects of environmental acidification on rainbow trout (Salmo gairdneri). J. Fish. Res. Board Can. 36: 84-87.

Rainbow trout exposed to acid without hypercapnia develop acidaemia which is not a result of anaerobic respiration. The increase in erythrocyte concentration probably offsets the effects of acidaemia upon blood oxygen carrying capacity.

227. Neville, C. M. 1979. Ventilatory response of rainbow trout (Salmo gairdneri) to increased H+ ion concentration in blood and water. Comp. Biochem. Physiol. 63A: 373-376.

The results indicate that without hypercapnia and whilst oxygen transport is adequate, there is no ventilatory response to increased internal or external H^+ ion concentration.

228. Neville, C. M. 1979. Influence of mild hypercapnia on the effects of environmental acidification on rainbow trout (Salmo gairdneri). J. Exp. Biol. 83: 345-349.

Rainbow trout were exposed to pH 4. Ambient and arterial P_{CO_2} were low, indicating acidaemia was not due to hypercapnia. Acidaemia is not due to lactic acid accumulation. Electrolyte loss is due to ambient low pH and not acidaemia.

229. Nichols, L. E., and F. J. Bulow. 1973. Effects of acid mine drainage on the stream ecosystem of the east fork of the Obey River, Tennessee. J. Tenn. Acad. Sci. 48: 30-39.

Approximately 40 mi of the east fork of the Obey River that was once highly productive with fish is now nearly devoid of fish and other aquatic life due to low levels of pH in the acid mine drainage from local mining activity.

230. Nisbet, I. C. T. 1974. Acid rain: fossil sulfur returned to earth. Mass. Inst. Techn. Tech. Rev. 76: 8-9.

Brief overview.

231. Odén, S. 1968. Nederbördens och luftens försurning dess orsaker, förlopp och verkan i olika miljöer. Statens Naturvetenskapliga Forskningsråd, Stockholm, Ekologikommitten, Bull. No. 1, 86 p. *

Thorough summary of the acid rain problem and the anticipated effects on aquatic and terrestrial ecosystems.

232. Odén, S. 1972. The extent and effects of atmospheric pollution on soils. FAO Soils Bull. 16: 179-194.

The effect of acid rain on some lakes is so strong that fish flee from these water systems and the spawn may not hatch. Lakes and rivers more permanently acidified are usually empty of fish.

233. Odén, S. 1976. The acidity problem - an outline of concepts. Water Air Soil Pollut. 6: 137-166.

An excellent review on acid precipitation.

234. Økland, J. 1969. Om forsuring av vassdrag og betydningen av surhetsgraden (pH) for fiskens naeringsdyr i ferskvann. Fauna 22: 140-147. *

Acidification of lake waters in Norway has resulted in adverse effects to fish-food organisms such as Gammarus lacustris at pH levels above those found directly harmful to fish.

235. ORSANCO. 1955. Aquatic life water quality criteria. Sewage Industr. Wastes 27: 321-331.

Reviews effects of pH on fish and aquatic organisms. Recommendations include that effluents should not alter pH levels outside the range 5-9, and as far as possible maintain values of pH 6.5-8.5.

236. Ottar, B. 1972. Säure Niederschläge in Skandinavien. Umschau 72: 290-291. *

The acidity of precipitation in Scandinavia is increasing and causing reductions of fish populations.

237. Packer, R. K. 1979. Acid-base balance and gas exchange in brook trout (Salvelinus fontinalis) exposed to acidic environments. J. Exp. Biol. 79: 127-134.

Brook trout were exposed to acidic environments and developed severe metabolic acidosis as shown by decreases in standard plasma bicarbonate levels as well as negative base excess values. Reduced oxygen consumption seen in acidic trout resulted from decreased gill oxygen transfer and reduced available blood oxygen capacity.

238. Packer, R. K., and W. A. Dunson. 1970. Effects of low environmental pH on blood pH and sodium balance of brook trout. J. Exp. Zool. 174: 65-72.

Brook trout exposed to a low environmental pH (3.0-3.3) showed a drop in mean blood pH from 7.39 to 6.97. Trout at an environmental pH of 3.5 lost 50% of their total body sodium. Control sodium influx (72.5 μmoles/100 g hours) decreased to zero between pH 3.0 and 4.9 as Na^+ efflux increased markedly over control levels. There was no significant difference in body Na^+ content of wild trout from three streams ranging in pH from 6.05-7.10. The inability of brook trout to live in waters of pH less than about 5.0 seems to be related to a drop in blood pH caused by the high hydrogen ion concentration of the medium. The loss of body Na^+ appears to be of secondary importance as a cause of death.

239. Packer, R. K., and W. A. Dunson. 1972. Anoxia and sodium loss associated with the death of brook trout at low pH. Comp. Biochem. Physiol. 41A: 17-26.

The lethal effect of H_2SO_4, HCl and acid mine water appears to be due to inhibition of O_2 uptake and to a large increase in net sodium loss.

240. Parsons, J. D. 1968. The effects of acid strip-mine effluents on the ecology of a stream. Arch. Hydrobiol. 65: 25-50.

Acid strip-mining in Missouri resulted in declines of zooplankton, benthic and fish populations, and numbers of species.

241. Parsons, J. D. 1976. Effects of acid-mine wastes on aquatic ecosystems. Proc. First Int. Symp. Acid Precipitation on the Forest Ecosystem, May 12-15, 1975, Columbus, Ohio. USDA For. Serv. Gen. Tech. Rep. NE-23: 571-595.

No fish were observed in Cedar Creek Basin, Missouri, in the area of continuous acid effluents from acid mine drainage. It is probable that degradation of such lakes can be reversed.

242. Parsons, J. W. 1952. A biological approach to the study and control of acid mine pollution. J. Tenn. Acad. Sci. 27: 304-309.

During heavy rains, acid mine drainage is flushed into relatively unpolluted streams resulting in fish kills and the movement of other fish downstream into unpolluted waters. Common creek chub have been found in a stream that ranged pH 4.3-5.6. Bluegills were found in a stream of pH near 4.5.

243. Pegg, W. J., and C. R. Jenkins. 1976. Physiological effects of sublethal levels of acid water on fish. West Virginia Univ., Morgantown Water Res. Inst. Bull. 6, 47 p.

The brown bullhead was more tolerant to low pH than either the bluegill or pumpkinseed fish. Rates of oxygen consumption of these three fish are also discussed.

244. Pentelow, F. T. K. 1944. Nature of acid in soft water in relation to the growth of brown trout. Nature, Lond. 153: 464.

In soft or acid water, spawning conditions are ideal for brown trout. Predatory fish are said to be absent in such waters which results in a large hatching percentage and high survival rate. However, the pressure on the available food source is great and therefore a general decrease in growth is observed in trout.

245. Pereira, J. R. 1926. On the influence of the hydrogen ion concentration upon the oxygen consumption in sea-water fishes. Biochem. J. 18: 1294-1296.

When sea water was acidified, _Fundulus heteroclitus_ appeared to close their mouths for long periods of time, thus avoiding contact with water over their gills. This corresponded with observed decreases in respiratory movement and lowered oxygen consumption in acidified sea water.

246. Peterson, R. H. 1979. The vulnerability of Charlotte County, N.B. lakes to acid precipitation, p. 17-18. _In_ Evaluation of recent data relative to potential oil spills in the Passamaquoddy area (D. J. Scarratt, ed.). Fish. Mar. Serv. Tech. Rep. 901.

Susceptibility of fish populations to acid precipitation in several lakes are discussed. Lakes in the Lepreau and Musquash drainages have no buffering capacity left and their fish populations are very susceptible to acidification.

247. Peterson, R. H. 1979. LRTAP: Effects on fishes. Proc. Long Range Transport of Air Pollution and its Impacts on the Atlantic Region, Oct. 17-18, 1979, Dartmouth, Nova Scotia, p. 83-85.

Research review. Also includes probably the first report of many rivers in southwestern Nova Scotia that once had salmon runs but are now barren of salmon, probably as a result of acid precipitation.

248. Peterson, R. H., P. G. Daye, and J. L. Metcalfe. 1980. Inhibition of Atlantic salmon hatching at low pH. Can. J. Fish. Aquat. Sci. 37: 770-774.

Hatching of Atlantic salmon eggs was delayed or prevented if they were exposed to water of lowered pH (4.0-5.5) after eye pigmentation had developed. Hatching could subsequently be induced by returning eggs to normal pH levels (pH 6.6-6.8). Perivitelline pH fell rapidly to near ambient levels when eggs were exposed to low pH. It is suggested that the observed effects on hatching were due to inhibition of the hatching enzyme, chorionase.

249. Peterson, R. H., P. G. Daye, and J. L. Metcalfe. 1980. Incubation of Atlantic salmon eggs: certain pH regimes may interfere with hatching. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

Eggs reared at low pH from fertilization had no delay of hatch. Eggs transferred to low pH during embryonal development had delayed hatching at pH 4.5-5.0 and inhibition of hatching at pH 4.0-4.2. Hatching could be induced for 10 d past normal hatching time by returning eggs to pH 6.8.

250. Petit, J., B. Jalabert, B. Chevassus, and R. Billard. 1973. L'insémination artificielle de la truite (_Salmo gairdneri_ Richardson). 1. Effets due taux de dilution, du pH et de la pression osmotique du dilueur sur la fécondation. Ann. Hydrobiol. 4: 201-210.

Dilute sea salt or NaCl at pH 9.5 and 255 mosmoles allows a dilution of trout sperm of 10^{-3} to 10^{-4} and was optimal for fertilization. A decrease to pH 8.4 and 7.3 caused a significant decrease in percentage of fertilization.

251. Plonka, A. C., R. B. Mitchell, and A. Anthony. 1971. Quantitative cytophotometry of PAS positive material in Stannius corpuscles of brook trout (Salvelinus fontinalis) exposed to acidic water. Proc. Pa. Acad. Sci. 45: 78-81.

A quantitative increase in PAS material in Stannius corpuscles was evidenced with acute but not subacute exposure to acid water.

252. Plonka, A. C., and W. H. Neff. 1969. Mucopolysaccharide histochemistry of gill epithelial secretions in brook trout exposed to acid pH. Proc. Pa. Acad. Sci. 43: 53-55.

Gills of trout exposed to acid water showed an increase in mucin content and a proliferation of cells between gill lamellae such that individual lamellae are indistinguishable.

253. Power, G. 1980. Acid rain. Atl. Salm. J. 29: 47-49.

Discussion includes the potential harm of acid rain on fishes, particularly Atlantic salmon, of eastern Canada.

254. Powers, E. B. 1921. Experiments and observations on the behavior of marine fishes toward hydrogen-ion concentration of the sea water in relation to their migratory movements and habitat. Publ. Puget Sound Biol. Sta. 3: 1-22.

The hydrogen-ion concentration of sea water does not control the behavior or migratory movements of fish.

255. Powers, E. B. 1922. The physiology of the respiration of fishes in relation to the hydrogen-ion concentration of the medium. J. Gen. Physiol. 4: 305-317.

The ability of marine fishes to absorb oxygen at low tension from sea water is more or less dependent upon the hydrogen-ion concentration of the water. The ability of fishes to withstand wide variations in hydrogen-ion concentrations of sea water can be correlated with the habitat. Fishes that are most cosmopolitan withstand wide pH variations while those that are least resistant to pH variation are the most restricted in their range of habitat. It is suggested that the variation in the ability to absorb oxygen at low tension at a given pH of individuals of a species is dependent upon the alkaline reserve of the blood of the individual fish.

256. Powers, E. B. 1930. The relation between pH and aquatic animals. Am. Nat. 64: 342-366.

Aquatic animals are able to withstand wide ranges of pH.

257. Powers, E. B., and G. A. Logan. 1925. The alkaline reserve the blood plasma of the viviparous perch (Cymatogaster aggregatus Gib.) in relation to the carbon dioxide tension, the oxygen tension, and the alkalinity of the sea water. Publ. Puget Sound Biol. Sta. 3: 337-360.

The alkaline reserve of the blood plasma of the perch was increased by a high CO_2 tension and decreased by a low CO_2 tension of the medium seemingly independent of the pH.

258. Pruthi, H. S. 1927. The ability of fishes to extract oxygen at different hydrogen ion concentrations of the medium. J. Mar. Biol. Assoc. U.K. 14: 741-747.

Ambient excessive hydrogen ions kill fish by interfering with their respiratory system, but this interference is independent on the amount of ambient oxygen. Therefore, fish do not die as a result of lack of oxygen in ponds and rivers where oxygen content is above 0.3 cc per liter.

259. Rahel, F. J., and J. J. Magnuson. 1980. Fish communities in naturally acidic lakes: examination of genetic adaptation to low pH. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

In naturally acidic small, northern Wisconsin lakes, only perch were found at pH's below 4.5. Healthy fish dominated by centrachids but no cyprinids were found at pH 4.6-5.0, cyprinids were found only in lakes above 5.0, and all fishes seemed able to tolerate levels greater than pH 5.5.

260. Reite, O. B., G. M. Maloiy, and B. Aasehaug. 1974. pH, salinity and temperature tolerance of Lake Magadi Tilapia. Nature 247: 315.

Tilapia were taken from their natural habitat of Lake Magadi where the pH was 9.8-10.1 and tested in acid waters. They survived waters of pH 5.0, showing no ill effects, but died in water of pH less than 5.0.

261. Roberts, B. A., and E. C. Jee. 1923. Report No. 36 (abridged) on the influence of hydrochloric acid and sodium hydroxide (caustic soda) on freshwater fish. Salm. Trout Mag. 32: 217-223.

Hydrochloric acid is relatively more toxic to perch and roach than sodium hydroxide. In an acid solution, roach are more resistant than perch. In an alkaline solution, roach and perch have similar resistance levels.

262. Robinson, G. D., W. A. Dunson, J. E. Wright, and G. E. Mamolito. 1976. Differences in low pH tolerance among strains of brook trout (Salvelinus fontinalis). J. Fish. Biol. 8: 5-17.

Survival time of brook trout at low pH was directly related to size, and inversely related to temperature. Inbred lines differed markedly providing strong evidence that acid tolerance is hereditary.

263. Ruby, S. M., J. Aczel, and G. R. Craig. 1977. The effects of depressed pH on oogenesis in flagfish Jordanella floridae. Water Res. 11: 757-762.

The ability of oocytes to form mature eggs is reduced at all levels below pH 6.7. This reduction is primarily produced by the loss of ability to deposit secondary yolk within the cytoplasm. At pH 4.5 both primary and secondary yolk deposition is severely affected. Retardation of oocyte growth reflects disturbances in protein production.

264. Ruby, S. M., J. Aczel, and G. R. Craig. 1978. The effects of depressed pH on spermatogenesis in flagfish Jordanella floridae. Water Res. 12: 621-626.

Mature male flagfish were tested for 20 d at pH levels of 6.0, 5.5, 5.0, and 4.5 with controls at pH 6.7. Production of mature sperm was reduced at all depressed levels of pH. Total volume of reproductive tissue relative to somatic tissue within the testes showed similar declines. A higher sensitivity of developing eggs to declining pH occurred when compared with developing sperm.

265. Runn, P., N. Johansson, and G. Milbrink. 1977. Some effects of low pH on the hatchability of eggs of perch, Perca fluviatilis L. Zoon 5: 115-125.

Eggs of perch were reared at different pH levels. At pH levels below 5.5 a reduction in hatchability was discerned and at pH 4.5 hatching was found only sporadically. In eggs reared at pH 5.0-4.5 the mortality up to the expected hatching date was low and 100% mortality was reached only after a prolonged non-hatched period 5-10 d later. The viability of the fry from the eggs reared at pH 5.0-4.5 was confirmed when eggs from this pH range were transferred to pH 7.3 at the normal hatching date and reached a hatching success close to that found for eggs reared at pH 7.3 throughout the period. After a prolonged non-hatched period the fry from eggs reared at and below pH 5.0 showed malformations. Histological studies indicate that the normal digestion of the chorion by choriolytic enzymes is disturbed at pH levels below 5.0.

266. Runn, P., and G. Milbrink. 1977. Early development of three salmonid species in acidified water. Zoon 5: 127-132.

Salmon are more pH sensitive than brown trout or brook trout. Because of its stationary habits brook trout could be a game fish to recommend for introduction in moderately acid river courses when the original fish fauna has been wiped out.

267. Ryan, P. M., and H. H. Harvey. 1977. Growth of rock bass, Ambloplites rupestris, in relation to the morphoedaphic index as an indicator of an environmental stress. J. Fish. Res. Board Can. 34: 2079-2088.

Acid precipitation of LaCloche Mountain lakes has reduced population densities of their fishes. Surviving rock bass responded to decreased abundance with increased growth rates. Authors suggest growth rate and mean lake depth may be used in a morphoedaphic index to indicate environmental stress.

268. Sanborn, N. H. 1945. The lethal effect of certain chemicals on freshwater fish. Cann. Trade 67, 3 p.

The upper lethal level of pH for goldfish is between 10.4 and 10.9.

269. Sano, H. 1976. The role of pH on the acute toxicity of sulfite in water. Water Res. 10: 139-142.

The toxicity of sulfite to fish decreases with increasing pH value, because the HSO_3^- ion is more toxic than the SO_3^{2-} ion.

270. Schofield, C. L. 1965. Water quality in relation to survival of brook trout, Salvelinus fontinalis (Mitchill). Trans. Am. Fish. Soc. 94: 227-235.

In Honnedaga Lake, periods of high acidity and heavy metals content during the summer were coincident with heavy mortality of brook trout transferred from both a hard-water and a soft-water hatchery.

271. Schofield, C. L. 1972. The ecological significance of air-pollution-induced changes in water quality of dilute-lake districts in the northeast. Trans. N.E. Fish Wildl. Conf., p. 98-112. Am. Fish. Soc. Ellenville, N.Y.

An overview of the acid rain problem with comments on the resultant effects to fish populations.

272. Schofield, C. L. 1976. Acid precipitation: Effects on fish. Ambio 5: 228-230.

Rapid extinction rates of fish populations inhabiting acidified waters have been observed over the past few decades in the Scandinavian countries and in parts of eastern North America. Extinction is often a result of chronic reproductive failure due to acidification induced effects during sensitive stages of the life-cycle.

273. Schofield, C. L. 1976. Lake acidification in the Adirondack Mountains of New York: causes and consequences. Proc. First Int. Symp. Acid Precipitation and the Forest Ecosystem, May 12-15, 1975, Columbus, Ohio. USDA For. Serv. Gen. Tech. Rep. NE-23, p. 477.

Fish populations have been adversely affected by acidification in approximately 75% of the high elevation lakes of the Adirondacks. Effects range from complete extinction of populations to alterations in density, size structure and growth rates.

274. Seip, H. M., and A. Tollan. 1978. Acid precipitation and other possible sources for acidification of rivers and lakes. Sci. Total Environ. 10: 253-270.

The trends in the recent acidification of rivers and lakes in southern Norway are reviewed. Brief attention is given to fish populations. The report indicated the southern rivers of Norway to have an acidity well above critical levels for salmon production.

275. Sevaldrud, I., I. P. Muniz, and S. Kalvenes. 1980. Loss of fish populations in southern Norway, dynamics and magnitude of the problems. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

A summary of data for past and present status of fish populations for about 5000 lakes in southern Norway affected by acidification.

276. Shelford, V. E. 1918. The relation of marine fishes to acids with particular reference to the Miles acid process of sewage treatment. Publ. Puget Sound Biol. Sta. 2: 97-111.

Sewage treated with H_2SO_4 and released into sea water is much more toxic to marine fishes than sewage effluents following treatment with SO_2.

277. Shelford, V. E. 1923. The determination of hydrogen-ion concentration in connection with fresh water biological studies. Bull. Ill. State Nat. Hist. Surv. 14: 379-395.

Fish tolerate a wide range and definitely react to hydrogen-ion concentrations in a manner similar to their reaction to temperature.

278. Shelford, V. E. 1925. The hydrogen ion concentration of certain western American inland waters. Ecology 6: 279-287.

Fish recognize differences in hydrogen ion concentration but the selection is relative rather than absolute.

279. Smith, H. W., and G. H. A. Clowes. 1924. The influence of carbon dioxide on the velocity of division of marine eggs. Am. J. Physiol. 68: 183-202.

CO_2 content rather than pH is important in modifying the velocity of division.

280. Smith, R. W., and D. G. Frey. 1971. Acid mine pollution effects on lake biology. Water Pollut. Cont. Res. Ser. 18050 EEC, EPA, Washington, D.C.

Six coal strip mine lakes in southern Indiana having a pH range of 2.5-8.2 were studied. Differences between lakes indicated successional trends with increasing pH. A fertilization program in one lake resulted in low fish populations.

281. Snekvik, E. 1969. Forsurning av elver og vann - Innvirkning på ørret-og laksefisket. Vann 3: 113-119.

The increasing acidity of lakes and rivers in southern Norway is described with the resultant effects on fishes.

282. Southern, R. 1932. The food and growth of brown trout. Salm. Trout Mag. 67: 168-176, 68: 243-258, 69: 339-344.

Trout grow better in alkaline waters as compared to acid waters.

283. Spaulding, W. M., and R. D. Ogden. 1968. Effects of surface mining on the fish and wildlife resources of the United States. Bur. Sport Fish. Wildl. Resour. Publ. 68, 47 p.

Surface mining has adversely affected fish habitats in 48 states, 12,898 mi of stream (135,970 surface acres), 281 natural lakes (103,630 surface acres), and 168 reservoirs and impoundments (41,516 surface acres) are involved. South Dakota reports 90% of its trout streams have been destroyed in the past 20 yr, and surface mining has been a major factor in the loss.

284. Sunde, S. E. 1926. Surt vand draeper laks-og ørretyngel. Norges Jeger-og Fiskeforb. Tidsskrift 2: 1-4. *

This report describes fish kills, apparently due to acid water, at hatcheries in southern Norway and the attempts to raise the pH by adding lime.

285. Surber, E. W. 1935. Effects of carbon dioxide on the development of trout eggs. Trans. Am. Fish. Soc. 65: 194-203.

The transplant of hatchery-reared trout to acid waters resulted in mass mortalities.

286. Swarts, F. A., W. A. Dunson, and J. E. Wright. 1978. Genetic and environmental factors involved in increased resistance of brook trout to sulfuric acid solutions and mine acid polluted waters. Trans. Am. Fish. Soc. 107: 651-677.

pH tolerance levels did vary among strains of brook trout. Prior exposure to nonlethal acidic conditions did not enhance resistance of brook trout. Embryonal development was delayed at low pH. The rate of net sodium loss at low pH was inversely correlated with the resistance times. There was no difference between the sexes in the survival times at low pH.

287. Swingle, H. S. 1957. Relationships of pH of pond waters to their suitability for fish culture. 9th Pac. Sci. Congr., Bangkok, Thailand, p. 102-103.

Waters ranging from pH 6.5-9.0 before daybreak are most suitable for pondfish culture. The acid death point for pondfishes is pH 4.0 and the alkaline death point is 9.0. Waters more acid than 6.0 give low fish production because zooplankton and important fish-food organisms fail to grow normally. Waters more alkaline than pH 9.5 yield low fish production because only small amounts of CO_2 are present in forms available to phytoplankton for photosynthesis.

288. Swynnerton, G. H., and E. B. Worthington. 1939. Brown trout growth in the Lake District. A study of the conditions in "acid" lakes and tarns. Salm. Trout Mag. 97: 337-355.

Brown trout grew well in acid lakes. Other chemical and biological parameters are discussed in terms of growth.

289. Tarzwell, C. M. 1957. Water quality criteria for aquatic life, p. 246-272. In Biological Problems in Water Pollution (C.M. Tarzwell,

ed.). U.S. Dept. Health, Education, and Welfare.

This review includes some effects of pH on fish.

290. Thommesen, G. 1975. Effekter på ørretens lukesans av kortvarige eksponeringer for surt miljø. SNSF-project, Norway IR 9/75, 17 p.

A short temporary decrease in the olfactory response of brown trout to stimuli resulted from short sublethal exposures to waters of pH 4.2-5.5.

291. Tomkiewicz, S. M., and W. A. Dunson. 1977. Aquatic insect diversity and biomass in a stream marginally polluted by acid strip mine drainage. Water Res. 11: 397-402.

If fish were able to survive in acid mine polluted waters of pH's between 4.5 and 5.0 they should find sufficient insect food for maintenance of a limited population.

292. Townsend, L. B., and H. Cheyne. 1944. The influence of hydrogen ion concentration on the minimal dissolved oxygen toleration of the silver salmon Oncorhynchus kisutch (Walbaum). Ecology 25: 461-466.

The pH of the water has a definite effect upon the ability of small silver salmon to withstand low dissolved oxygen concentrations. Near the limit of low dissolved oxygen concentration tolerance, increasing the hydrogen ion concentration produces the same effect as lowering the oxygen.

293. Trama, F. B. 1954. The pH tolerance of the common bluegill (Lepomis macrochirus Rafinesque). Not. Nat. Philadelphia 256: 1-13.

The upper and lower LL50 of pH for the bluegill is pH 10.35 and 4.0, respectively.

294. Trojnar, J. R. 1977. Egg and larval survival of white suckers (Catostomus commersoni) at low pH. J. Fish. Res. Board Can. 34: 262-266.

White sucker (Catostomus commersoni) eggs were incubated in water of high (250 μmhos/cm) and low (20 μmhos/cm) conductivity with nominal pH ranging from 4.2-8.0. At pH 4.5 and below in water of low conductivity no eggs survived to hatching. In high conductivity water at pH 4.5 a few prolarvae hatched but were deformed and soon died. At pH 5.0 and above the total hatch was the same at either conductivity level. However, at pH 5.0 there were body deformities and abnormalities in the vascular system and none of the prolarvae survived to the swim-up stage. At both conductivity levels there was a reduction in swim-up at pH 5.3 compared with the control, but none at pH 5.8. Low pH had a delaying influence on the absorption of the yolk sac.

295. Trojnar, J. R. 1977. Egg hatchability and tolerance of brook trout (Salvelinus fontinalis) fry at low pH. J. Fish. Res. Board Can. 34: 575-579.

Hatchability of brook trout eggs incubated at pH 4.6, 5.0, 5.6, and 8.0 ranged from 76-91%. Author suggests an acclimation effect occurs. No fry incubated at mean pH 8.07 survived mean postemergent pH 4.00 while more than 60% of those incubated at all other pH levels survived.

296. Tsai, S., C. M. Boush, and F. Matsumura. 1975. Importance of water pH in accumulation of inorganic mercury in fish. Bull. Environ. Contam. Toxicol. 13: 188-193.

Inorganic mercury at high pH values was not as readily translocated from water into fish as at low pH conditions, even though abundant in high pH waters. The cause of such a reduction might be related to those unreactive forms of mercury complexes formed under alkaline conditions.

297. Turner, W. R. 1958. The effects of acid mine pollution on the fish populations of Goose Creek, Clay County, Kentucky. Prog. Fish-Cult. 20: 45-46.

A tributary of the Kentucky River was polluted with acid waters from an operating coal mine, resulting in a fish loss of 92% of the population in the polluted area.

298. Ultsch, G. R. 1978. Oxygen consumption as a function of pH in three species of freshwater fishes. Copeia 1978: 272-279.

Results suggest that the importance of anoxia as a factor contributing to the death of fishes at low pH may vary among species.

299. Ultsch, G. R., and G. Gros. 1979. Mucus as a diffusion barrier to oxygen: possible role in O_2 uptake at low pH in carp (Cyprinus carpio) gills. Comp. Biochem. Physiol. 62A: 685-689.

The standard V_{O_2} of carp is reduced at low pH concurrently with the formation of mucus on the gills. It was concluded that mucus on the gills contributes to the hypoxia observed in fish subjected to high acidities.

300. Vaala, S. S., and R. B. Mitchell. 1970. Blood oxygen-tension changes in acid-exposed brook trout. Proc. Pa. Acad. Sci. 44: 41-44.

Oxygen-tension of the venous blood from the heart ventricle of brook trout was significantly reduced in acid exposed fish. Compensatory erythrocytic changes are associated with decreased blood oxygen tension.

301. Vaala, S. S., R. B. Mitchell, and A. Anthony. 1969. Cytophotometric studies of DNA in circulating erythrocytes of brook trout exposed to acid pH. Proc. Pa. Acad. Sci. 43: 191-194.

Brook trout exposed to low pH (3.5) for 4 d accumulate excessive PAS-positive mucin notably in the gill region. No evidence was found of either enhanced hemopoiesis or increased rate of red cell destruction in acid-water exposed fish.

302. Warner, R. W. 1971. Distribution of biota in a stream polluted by acid mine drainage. Ohio J. Sci. 71: 202-215.

Roaring Creek of eastern West Virginia had fish populations inhabiting only those reaches of the stream where the median pH was 4.9 or higher. Fish found were brook trout, mottled sculpin, blacknose dace and creek chub.

303. Watanabe, T., H. Kamijo, I. Morishita, T. Shinya, and K. Mashiko. 1973. Studies on the eutrophication of Lake Osoresan-ko, a remarkable inorganic acidotrophic lake in Japan. Ann. Rep. Noto Mar. Lab. 13: 39-51.

Lake Osoresan-ko is an acidotrophic lake in Japan with a pH range of 3.0-4.0 in the main part of the lake. High acidity is due to inflow of sulphuric acid from nearby hot-springs. The teleost, Tribolodon hakonensis, is the only fish in these waters, but it is very abundant.

304. Wells, M. M. 1915. Reactions and resistance of fishes in their natural environment to acidity, alkalinity and neutrality. Biol. Bull. 29: 221-257.

Freshwater fishes select slight acidity in a gradient when the other choices are neutrality and alkalinity. They choose slight alkalinity in preference to neutrality.

305. Westfall, B. A. 1945. Coagulation film anoxia in fishes. Ecology 26: 283-287.

The lethality of sulfuric acid to goldfish results from decreased permeability of the gill membrane system to oxygen as a result of the precipitation of mucus on the gill filaments.

306. Wiebe, A. H. 1931. Notes on the exposure of several species of pond fishes to sudden changes in pH. Trans. Am. Micro. Soc. 50: 380-393.

The ability of several species of fish to tolerate rapid and extensive changes in ambient pH were studied. Apomotis cyanellus tolerated changes from pH 7.2-9.6 and 8.1-6.0. Goldfish tolerated changes from pH 7.2-9.6. Fry and fingerlings of Micropterus dolomieu and M. salmoides tolerated changes of 3.1 pH units.

307. Wiebe, A. H. 1931. Notes on the exposure of several species of fish to sudden changes in the hydrogen-ion concentration of the water and to an atmosphere of pure oxygen. Trans. Am. Fish. Soc. 61: 216-224.

Fish can tolerate a wide range of pH.

308. Wiebe, A. H., A. M. McGavock, A. M. Fuller, and H. C. Markus. 1934. The ability of freshwater fish to extract oxygen at different hydrogen-ion concentrations. Physiol. Zool. 7: 435-448.

Several species of freshwater fish: largemouth blackbass, smallmouth blackbass, white crappie, yellow perch, rainbow trout, goldfish and green sunfish have the ability to extract oxygen from water at low oxygen tensions equally well over a fairly wide range of hydrogen-ion concentrations. The bluegill has a somewhat narrower range of toleration. Two species of minnow - steel-colored and bluntnose - tolerate a markedly narrower range of difference in hydrogen-ion concentration. The ability of fish to extract oxygen from the water at low pressure depends more or less on the hydrogen-ion concentration of the water. In highly alkaline water fish require a higher concentration of oxygen to survive.

309. Witschi, W. A., and C. D. Ziebell. 1979. Evaluation of pH shock on hatchery-reared rainbow trout. Prog. Fish-Cult. 41: 3-5.

Results indicate that it is not advisable to stock rainbow trout reared in nearly neutral hatchery water into lakes with a pH of 9.0 or higher.

310. Wollitz, R. E. 1972. The effect of acid mine drainage on the limnology of a small impoundment in southwest Virginia. Proc. 26th Ann. Conf. S.E. Assn. Game Fish Comm.: 442-460.

Extensive fish mortalities and the reduction of the fishery of some Virginia waters in February of 1969 and 1970 appear to be due to the toxicity of copper, mercury, zinc and to some extent the toxicities of iron, manganese and/or low pH, and low carbonate alkalinity.

311. Wright, R. F. 1976. Acid precipitation and its effects on freshwater ecosystems. An annotated bibliography, p. 619-678. In Proc. First Int. Symp. Acid Precipitation and the Forest Ecosystem (L. S. Dochinger and T. A. Seliga, eds.). USDA Forest Serv., Gen. Tech. Rep. NE-23.

312. Wright, R. F., T. Dale, E. T. Gjessing, G. R. Hendrey, A. Henriksen, M. Johannessen, and I. P. Muniz. 1976. Impact of acid precipitation on freshwater ecosystems in Norway. Water Air Soil Pollut. 6: 483-499.

Increasing acidity of freshwaters causes interference at every trophic level. Decomposition of organic matter is inhibited, the species number of phyto- and zooplankton and benthic invertebrates decreases, and the growth of benthic mosses is promoted. Fish populations are severely affected, the salmon have been eliminated from major rivers, and hundreds of lakes have lost their sport fisheries.

313. Wright, R. F., and E. T. Gjessing. 1976. Acid precipitation: Changes in the chemical composition of lakes. Ambio 5: 219-223.

Fresh waters in large areas of northern Europe and eastern North America that are receiving acid precipitation appear fated to suffer acidification, loss of fish populations and disturbance of other vital ecosystem components and processes.

314. Wright, R. F., A. Henriksen, R. Harriman, B. Morrison, and L. A. Caines. 1980. Acid lakes and streams in the Galloway area, southwestern Scotland. Int. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, March 11-14, 1980.

The loss of fish populations from soft- and poorly buffered waters in this area of Scotland has occurred because of the deposition of strong acids from the atmosphere.

315. Wright, R. F., and E. Snekvik. 1978. Acid precipitation: chemistry and fish populations in 700 lakes in southernmost Norway. Verh. Intern. Verein. Limnol. 20: 765-775.

Fish populations (mainly brown trout) have been eliminated from about 40% of these lakes and an additional 40% have sparse populations. Since the reproductive process is the most sensitive to acid stress, these data indicate that recruitment has completely or partially failed in 80% of the lakes in Sørlandet. Multiple regression analysis of fish and chemical data indicates that pH and Ca are the two most important chemical parameters related to fish status. Ca^{++} apparently ameliorates acid stress, probably by reducing Na loss from the fish.

316. Wuhrmann, K., and H. Woker. 1948. Beiträge zur toxikologie der fische. II. Experimentelle untersuchungen über die ammoniak-und blausäurevergiftung. Schweiz. Zeitschr. Hydrol. 11: 210-244.

The toxicity of free ammonia in water to fish is determined by its pH and by the concentration of the ammonia salt. Molecular ammonia is more toxic than ammonium ions.

SUBJECT REFERENCE

GEOGRAPHIC REFERENCE