Scientific Stream Pollution Analysis

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PREFACE

It is with deep humility that I give you a textbook on this vast and comprehensive subject. I do not profess to be an expert on all aspects of stream evaluation. But, on the other hand, few if any persons now living can claim in all honesty to be such an expert. At the same time I recognize that my students, as well as workers worldwide, urgently need to be aware of every major facet of stream analysis.

The first five chapters represent the foundation for all modern stream analysis. One could consider each chapter an ample subject for an entire book. Therefore each of these chapters contains selective rather than comprehensive coverage of all the material available. If a student masters the subsection theories presented in each chapter, he should be in a position to comprehend most other subjects of important significance to the major theme of the chapter.

In the past, and even at the present, too many scientists and engineers treat the subject of stream analysis as a single discipline, to be solved either with a biological survey, or a chemical series of analyses, or simply by a dissolved-oxygen survey. Students in today's analyses of streams programs also might presume, erroneously the single discipline approach. Therefore, this text was written with a view toward overcoming this false presumption. The writer has observed more than once that "highly polluted" streams often show no oxygen sag characteristic at the time of analysis. Only a biological analysis would confirm the fact of pollution. On the other hand a biological analysis seldom, if ever, provides the analyst with design criteria with which to overcome the polluted state of the stream. In the first three chapters I have endeavored to give equal emphasis to the biological, hydrological, and biochemical aspects of stream analysis. I recommend that the reader complete all three chapters before he decides how to undertake a comprehensive survey of a particular receiving water. In Chaps. 4 and 5, I have presented the mathematics of computing first the deoxygenation rate and then the reaeration rate—commonly referred to as stream reaction rates. Next they are considered collectively in Chap. 6 in order to plot the oxygen concentration profile for a stream receiving some organic wastewater. Although many procedures are given for computing k_1 (the deoxygenation rate), k_2 (the reaeration rate), and the oxygen sag curve plots, a summary of the author's recommended procedures is also given in Chap. 6. In order to relate these stream analyses to acceptable or rejectable water quality levels, I have included the rather long and controversial Chap. 7 on receiving water quality objectives. Since many contaminants are being discharged near or in estuarine waters, and since more and more multi-purpose uses are being made of these special waters, I describe in Chap. 8 two generally used techniques for analyzing estuarine waters. No pollution abatement program is successful without the proper administration of the stream resources. Since our first major federal legislation in 1948, some evidence of this fact can be observed in the United States. Adminstration of these resources from many different viewpoints and by many political entities is described in Chap. 9. I have even taken an author's liberty of submitting my proposed administrative system of marketing stream-pollution-capacity resources in this chapter. In case the reader believes that carrying out the doctrines described in the first six chapters is an easy one, solved only by routine sampling and analysis, I suggest he follow the practical illustration given in Chap. 10. Here the frustrations of a stream analyst are vented for public display and consideration. The mistakes of an analyst are not easily forgotten by the reader, but successful undertakings, on the other hand, are likely to be taken as normal practice and easily overlooked. The purpose of this chapter is not to discourage the stream analyst, but to encourage him to use all his knowledge and scientific tools in analyzing and evaluating the condition of a receiving water in the most equitable and proper manner possible.

I would like to thank all researchers who have taken the time and made the effort to write, either in paper or text form, their ideas and experiences in stream analysis. From them I have gained much foresight and information. Equally vital, however, have been the last 25 years spent sampling, analyzing, and assessing the pollution capacity of many of our streams, rivers, and lakes. Experiences in these endeavors, although not always entirely satisfactory, still make for excellent teachers.

Many of my graduate students have labored over semifinished material from these chapters distributed during their classes. Their suggestions for improving clarity and content are deeply appreciated. They can take pride in knowing that their contributions will help future generations of students.

Once again I have prevailed upon the patience of my wife, Joan, who persevered while I spent the long hours writing. The assistance of Mrs. Vola Tietge in typing the major portion of the manuscript is acknowledged with appreciation. The inspiration of my father-in-law, Benjamin E. Botway, throughout the writing of the book and in selecting its title were important factors in its completion.

Nelson Leonard Nemerow

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Chapter 1

BIOLOGICAL ASPECTS OF STREAM SANITATION

The biological consequences of stream pollution often persist long after the evidence of physical or chemical contaminants has disappeared. For this single reason streamwater quality evaluations must include a detailed biological analysis. Therefore, the stream analyst familiarizes himself with the basic biological parameters and phenomena which are involved. The intent of this chapter is to provide the reader with a description of the role of biology in stream pollution evaluation.

1-1. BACTERIAL GROWTH PHASES IN STREAMS

Water pollution control investigators have understood for more than two decades that bacterial growth proceeds in continuous phases. One popular system describes this growth as occurring in seven distinctly separate and significant phases. It is shown graphically in Figure 1-1. The sigmoid growth curve is very useful, since by analyzing a stream microbiologically we can obtain a good indication of our location on a relative pollution scale. However, this curve is many times more "ideal" than "real."

Butterfield (1929b, 1931) found that when he grew bacteria in a series of flasks in which the food concentration was progressingly varied the numbers of bacteria always rose rapidly to a fixed ceiling, after which they remained stationary or slowly declined; reducing the bacterial population by filtration, chlorination, or heating restored the high rate of biochemical activity, and the population again rose toward the ceiling value. The ceiling value was definitely related to the food concentration, although the buildup of metabolic waste products may also influence the ceiling value of bacterial numbers. He also found that it was the rate of growth of the bacteria, rather than their mere numbers, that determined the rate of oxidation. When the population became static at exceedingly high numbers, the rate of oxidation became nearly zero, showing that oxidation results only from bacterial growth and vice versa.

In its early stages, with a constant rate of multiplication per unit of population, the process is autocatalytic in that the rate of addition of new individuals is proportional to the total population, which is progressively

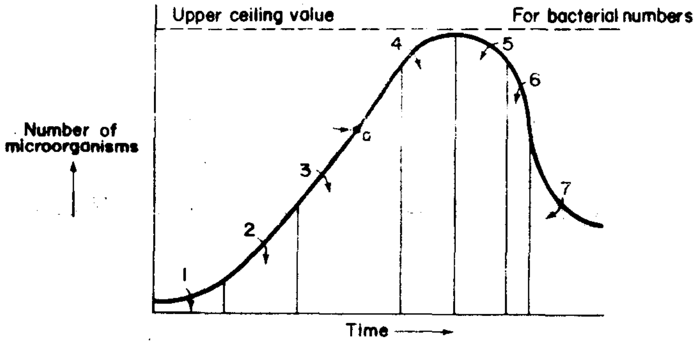

FIG. 1-1. Bacterial growth phases. a = Maximum rate of increase; 1 = Stationary phase; 2 = Accelerated growth phase; 3 = Logarithmic growth phase; 4 = Decreasing growth phase; 5 = Negative growth phase; 6 = Accelerated death phase; 7 = Logarithmic death phase.

increasing. This is the well known exponential or geometric rate of increase in population (see Fig. 1-1(3)).

$N(t) = Ae^{kt}$ where A = a constant
$N(t)$ = No. of bacteria at time t
$k = \log a$

Ultimately overcrowding occurs—a situation which can be best described as one exceeding the carrying capacity of the stream due to lack of food supply and accumulation of toxic metabolic products. The population changes from an increasing rate of growth to a decreasing one approaching, finally, an upper ceiling value.

The important fact to remember is that at the midpoint in the growth curve (see Fig. 1-1, pt. a) there is a maximum rate of increase. The rate of increase increases for the duration of exponential growth. When the bacterial population is kept somewhere near this midpoint where mortality equals reproduction, the rate of multiplication remains proportional to the actual food concentration (organic matter). Underlying this relationship is the theory of the Biochemical Oxygen Demand (BOD) reaction, in which oxygen is used up by microorganisms in direct proportion to the organic matter remaining.

Predators such as protozoa help to keep the bacterial numbers at the logarithmic growth phase. If the food concentration were constantly replenished, an equilibrium would exist between the bacterial numbers and rate of oxidation. This is why we continuously add soluble food to a sewage oxidation pond. However, in a laboratory BOD bottle and in a stream contaminated with organic matter at one point and undergoing self purification, the food concentration is being continuously reduced downstream from the point of contamination. *Thus there is a continual readjustment of the bacterial population to the steadily decreasing food supply, in which the rate of bacterial reproduction is automatically maintained at a maximum level and about in* *proportion to the concentration of available food.* This phenomenon is shown in Fig. 1-2.

We have just shown how bacteria live, grow, multiply, and die under conditions where a good deal of food is usually present. However, there is one barrier to this oxidation of organic matter which the bacteria carry out: the death rate of the bacteria themselves. It is generally accepted today that bacteria of all types, and especially those of intestinal origin, tend to die out, even under conditions of gross pollution. It is common knowledge that storage, whether it be in a flowing river or an impounded reservoir, eliminates organisms of sewage origin and other bacteria as well. The death rate appears to be a function of time modified by a marked temperature coefficient.

In the ideal situation when no toxic elements are present, bacteria die in a logarithmic phase. Therefore, they die at a rate according to the numbers of organisms remaining. They don't quite match the logarithmic portion of the death curve, because some of the organisms remaining are more resistant than the ones that died off in earlier stages (see Fig. 1-1.) The rate of decrease is more rapid at higher temperatures, the initial rate of increase is greater (see Fig. 1-3), since bacterial growth is enhanced as temperature rises to about 40°C. Generally in summer the flow in a stream is low and sedimentation occurs, whereas in winter sedimentation is lower in the areas of increased velocity of flow. Thus, more bacteria will settle to the bottom in summer than in winter, and the BOD bottle in the laboratory will be a better representation of natural conditions in the winter.

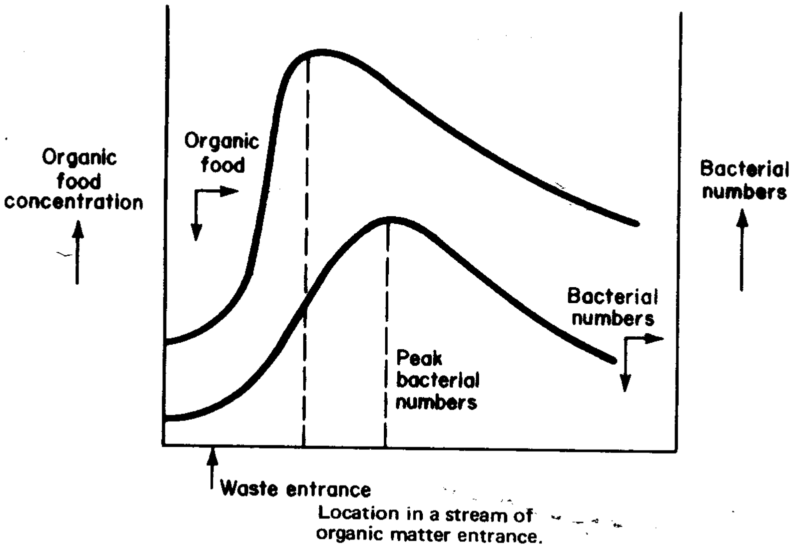

FIG. 1-2. Bacterial self purification as related to watercourses.

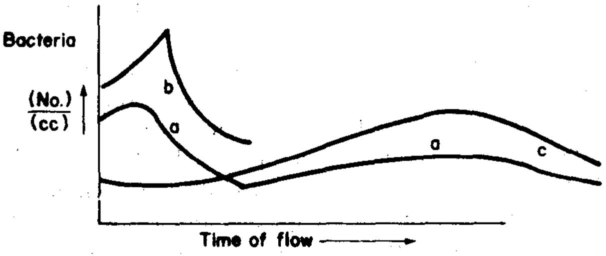

FIG. 1-3. Comparative growth of microorganisms under winter and summer conditions ((a) = stream; (b) = summer conditions (higher temperature) BOD bottles; (c) = winter conditions (lower temperatures) BOD bottles).

Two general types of bacteria are described by Heukelekian (1953) as present in a stream: the *native water population* and the *pollutional forms*, such as coliform microorganisms. In the biochemical oxidation of the pollution, the coliform organisms play only a minor role. The slight increase in bacteria below a sewer outlet is said to be due most probably to possible multiplication or dispersion of bacterial aggregates. The decrease in numbers thereafter parallels the decrease of organic material by oxidation.

The forces that affect the decrease of bacterial numbers in a stream are:

1. *Sedimentation.* Bacteria slowly settle and attach themselves to other aggregates which settle faster. This results in an apparent decrease in bacterial numbers in the flowing water.
2. *Protozoa.* Ciliated protozoa ingest bacteria.
3. *Food supply.* Not as abundant as in culture medium. Coliform organisms inoculated into sterile sewage will not multiply or transform organic materials, which shows the relatively poor food value of sewage for coliform bacteria only. Food is always decreasing due to oxidation.
4. *Stream temperature.* Below optimum for growth of pollutional bacteria even in summer. Higher temperature stimulates bacterial growth in presence of adequate food and favorable environmental conditions (see Fig. 1-4). A 10°C

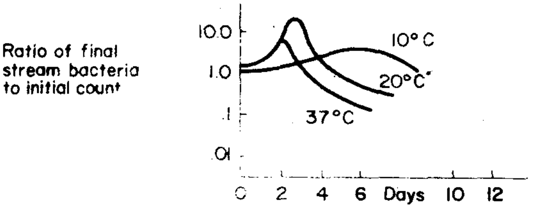

FIG. 1-4. Effect of temperature on bacterial growth. *20°C appears to be near an optimum for the growth of stream bacteria.

rise in temperature results in an approximate doubling of the biological reaction rate.

5. *Sunlight.* Sunlight has bactericidal properties but is probably insignificant because of the poor penetration of ultraviolet rays, especially in turbid waters.

6. *Bacteriophage.* Destruction of bacteria by the lytic action of virus-like bacteriophage, which is parasitic on bacteria. However, this lysis occurs only when rapid multiplication of bacteria exists. (Therefore, it does not exist for intestinal groups of bacteria in receiving waters).

7. *Industrial waste.* Seldom contributes many bacteria and mostly results in an immediate and sharp decrease in numbers. Some exceptions exist, such as in potato and other food product wastes.

8. *Dilution* of both food and bacteria by streamwater.

Butterfield's contribution to basic bacteriological stream phenomena

Until his retirement in 1951, C. T. Butterfield was quite active in the field of sanitary microbiology. His main work in this field deals with the aspects of water microbiology and the interrelationship of bacteria and protozoa. His work with activated sludge and trickling filtration will not be considered here. Some of his major findings and areas of research are:

1. He advanced the theory that the chief function of certain zooplankton in the biochemical oxidation process is to keep the bacterial population reduced below the saturation point and thus to provide conditions suitable for continuous bacterial multiplication, which in turn results in more complete oxidation.
2. Both the rate and extent of oxidation are increased if bacteria are kept dispersed throughout the medium such as in a completely mixed activated sludge treatment system.
3. Bacterial processes are the same regardless of whether the water is moderately or grossly polluted. However, the species of bacteria acting and their method of operation vary. In moderately polluted waters the bacteria are of the type which grow uniformly dispersed. In grossly polluted waters under maintained aerobic conditions the bacteria are of the type that grow in masses or colonies. This latter type is capable of increased purification efficiency due to its mode of growth and adsorptive extracellular capsular substance.

Since his work is basic to much of our biological consideration on stream pollution, the major references containing his work are listed at the end of this chapter. The reader—especially one who would advance the biological concept of stream assessment—is urged to examine Butterfield's work in more detail.

1-2. ZONES OF STREAM REACTION TO POLLUTION

One effect of bacterial growth in streams has been to create definitive and distinguishable stretches below a source of organic pollution. One of our earlier stream analysts, F. J. Brinley (1942), classifies streams receiving-wastes into five separate zones. These are described in summarized form as follows:

Zone I – zone of active bacterial decomposition

This zone is immediately below the source of pollution and is usually characterized by a low dissolved oxygen (0–3 ppm), especially during critical low flows, a high biochemical oxygen demand, a high bacterial count, the presence of bacteria-eating protozoa such as *Paramecium, Colpidium, Vorticella,* and *Carchesium,* and a few flagellates. The total number of plankton forms is low. *Tubifex* and *Liminodrilus* worms are found in the bottom deposits. Gas evolution often brings sludge to the surface. Sewage fungus is present. Only a few coarse fish such as carp and buffalo are found at the mouth of the sewer.

Zone II – zone of intermediate bacterial decomposition

The rate of biochemical respiration decreases in this zone, and as a result the dissolved oxygen goes up to 3–5 ppm. The plankton volume is higher, but the plankton is still made up of pollutional forms requiring a rich medium of bacteria and solid particles for feeding. There is an increase in green and blue-green algae forms. In addition to carp and buffalo, shiners, minnows, suckers, and sunfish are found.

Zone III – recovery

The water gradually becomes clearer, green plants reappear, small animals serve as food for fish. Oxygen increases and fish return.

One of the difficulties with this classification is that the first two zones are rather arbitrary and subjective. It is often impossible to distinguish between Zone I and II as defined above. However, it is apparent that a determination of the appearance can reveal considerable information about the realtive pollution of a stream.

The length of any biological zone of a stream is also affected by the physical characteristics such as stream gradient. These are more fully described in Chapter 2.

Patrick's Biological Measures of Stream Conditions

It is a well known fact that in a normally healthy stream there is a biodynamic cycle which results in a balance of plant and animal life. The effect of sanitary and industrial pollution is to alter this cycle. Patrick believes that because the physical, chemical, and environmental characteristics in a stream are so variable, tests involving these would not accurately predict the effects of an effluent on a given stream (1950). She has developed a system of observing organisms in streams and assuming the degree of pollution from an analysis of the groups and relative numbers present.

Patrick created seven different taxonomic groups of organisms to be used as biological measures of stream conditions:

1. The blue-green algae, some green algae, some rotifers
2. Oligochaetes, leeches, snails
3. Protozoa
4. Diatoms, red algae, and most of green alagae
5. All rotifers not in (1) plus clams, worms, and some snails
6. All insects and crustacea
7. All fish

From observations and enumerations of the seven groups she has arrived at five classifications of a river:

1. *A Healthy Stream.* Balance of organisms: the algae are mainly diatoms and green algae; the insects and fish are represented by a variety of species. Four, 6, and 7 (above) are all above 50% level, based upon levels found in a natural station upstream.

2. *A Semi-Healthy Stream.* Balance somewhat disrupted. Pattern is an irregular one; a given species will be represented by a greater number of individuals. The following possibilities may appear: either of both 6 and 7 (above) below 50% and 1 and 2 under 100%. Either 6 or 7 below 50% and 1, 2, and 4 100% or above; or 4 is double width column (one which has many more species than normal), resulting in the dominance of a single organism.

3. *Polluted.* Stream in a condition in which the balance of life found in a healthy station is upset. However, conditions are favorable for some groups of organisms such as 1 and 2. The following may be observed: species of either or both 6 and 7 are absent, and 1 is 50% or better. Species of 6 and 7 are both present but below 50%, so that column 1 and 2 must be 100% or more.

4. *Very Polluted.* Stream in a condition that is definitely toxic to plant and animal life. Often many groups may be absent. This state occurs if 6 and 7 are absent and 4 is below 50%, or if 6 and 7 are present but 1 or 2 is less than 50%.

5. This group is *atypical* because it cannot be compared, either due to general ecological conditions or to methods of collection, to the healthy stations used as a basis; i.e., healthy stations may be in eutrophic conditions, while cool oligotrophic water could hardly be rated on the same basis. Likewise, a stream with a steep, newly eroded bank would not be comparable with a normal stream with shallow water near edges. The extent of sampling and the competence of the laboratory technicians will undoubtedly influence the final decision of the classification of the stream.

Patrick concludes that the general effect of pollution seems to be a reduction in species number, with the most tolerant surviving. It is also interesting to note that groups 3 and 5 are not used specifically in defining any of the above five classifications.

In relation to stream sanitation, Dr. Patrick did propose a method for measuring stream conditions by the presence or absence of species of all major groups that play a role in the biodynamic cycle of the stream, instead of the classical examination of the physical and chemical characteristics of the streamwaters. In Dr. Patrick's method the bacteria and fungi present are considered only as to total count and as indicator organisms, respectively.

This method was based on a survey conducted on the Conestoga basin in Lancaster County, Pennsylvania, in 1949. The area comprises about 475 square miles with a bedrock of limestone and shale and has a "rolling" topography. It is intensively farmed and has many streams, the margins of which are bordered by cultivated fields. There are, however, some industrial and residential areas in the basin, so that while some streams receive only farmhouse wastes, others receive industrial and sanitary wastes. The larger streams are usually turbid, owing to the erosion of clay soil, and the waters are of eutrophic type. At each stream two stations were selected: one station was to determine general conditions, and a riffle, slack water, and a pool were included; the second station was used to determine the effect of an effluent on the stream by studying and comparing the ecological condition just below the confluence with those above it. Samples of water, mud, and of the various organisms were taken at each of the 77 stations and identified with the assistance of 22 scientific consultants. The organisms so found were grouped into seven columns as listed on page 7.

At each of the stations the results of chemical analysis for different times and a species list of bacteria were obtained. Histograms were prepared for each of the stations, and, based on them, five general classifications of streams were prepared (also listed on page 7).

The results show that toxic agents, and not depletion of dissolved oxygen, cause the most damage to plant and animal life in the streams. Although none of the stations had a limiting amount of dissolved oxygen, those subjected to toxic effects showed an alteration in their biodynamic cycle ranging from a reduction in taxonomic groups to a complete lack of animal and plant life.

All indications point to the fact that in a healthy stream a great many species should be present, but no one species should be predominant. The effect of pollution seems to be a reduction in the number of species, with an increasing abundance of individual species among those surviving. Therefore, the percentage present or the absence of taxonomic groups can be used as an index of stream pollution, since healthy streams require a balanced physiological activity. Moreover, this method reflects the conditions existing over a period of time and not at the moment of sampling, as may occur in the case of physical and chemical analyses. However, the use of bioassays to evaluate streams may be preferable in some cases to a lengthy stream biological analysis. The latter is often time-consuming and quite costly without providing all the answers required by the stream analyst.

Since her work deserves to be read by all advocates of the biological system of stream classification, a list of many of Patrick's most valuable references will be found at the end of this chapter.

MacKenthum (1969) gives an excellent graphic picture (see Fig. 1-5) of the kinds and numbers of animal life found in typical streams following the introduction of organic, toxic, and inert forms of pollution.

Palmer (1962) gives an enumeration of both clean water forms of algae and algae associated with organically enriched watercourses.

Clean Water Algae

Group and Algae

- Blue-Green Algae *(Myxophyceae)*:
  - *Agmenellum quadruplicatum, glauca type*
  - *Calothrix parietina*
  - *Coccochloris stagnina*
  - *Entophysalis lemaniae*
  - *Microcoleus subtorulosus*
  - *Phormidium inundatum*
- Green Algae *(Nonmotile Chlorophyceae)*:
  - *Ankistrodesmus falcatus, var. acicularis*
  - *Bulbochaete mirabilis*
  - *Chaetopeltis megalocystis*
  - *Cladophora glomerata*
  - *Draparnaldia plumosa*
  - *Euastrum oblongum*
  - *Gloeococcus schroeteri*
  - *Micrasterias truncata*
  - *Rhizoclonium hieroglyphicum*
  - *Staurastrum punctulatum*
  - *Ulothrix aequalis*
  - *Vaucheria geminata*
- Red Algae *(Rhodophyceae)*:
  - *Batrachospermun vagum*
  - *Hildenbrandia rivularis*
  - *Lemanea annulata*
- Diatoms *(Bacillariophyceae)*:
  - *Amphora ovalis*
  - *Cocconeis placentula*
  - *Cyclotella bodanica*
  - *Cymbella cesati*
  - *Meridion circulare*
  - *Navicula exigua var. capitata*
  - *Navicula gracilis*

Pollution Algae—Algae Common in Organically Enriched Areas

Group and Algae

- Blue-Green Algae *(Myxophyceae)*:
  - *Agmenellum quadruplicatum, tenuissima type*
  - *Anabaena constricta*
  - *Anacystis montana*
  - *Arthrospira jenneri*
  - *Lyngbya digueti*
  - *Oscillatoria chalybea*
  - *Oscillatoria chlorina*
  - *Oscillatoria formosa*
  - *Oscillatoria lauterbornii*
  - *Oscillatoria limosa*
  - *Oscillatoria princeps*
  - *Oscillatoria putrida*
  - *Oscillatoria tenuis*
  - *Phormidium autumnale*
  - *Phormidium uncinatum*
- Green Algae *(nonmotile Chlorophyceae)*:
  - *Chlorella pyrenoidosa*
  - *Chlorella vulgaris*
  - *Chlorococcum numicola*
  - *Scenedesmus quadriccula*
  - *Spirogyra communis*
  - *Stichococcus bacillaris*
  - *Stigeoclonium tenue*
  - *Tetraedron muticum*
- Diatoms *(Bacillariophyceae)*:
  - *Gomphonema parvulum*
  - *Hantzschia amphioxys*
  - *Melosire varians*
  - *Navicula cryptocephala*
  - *Nitzschia acicularis*
  - *Nitzschia palea*

(Continued on page 11)