Water Quality for Aquaculture and Fisheries Students

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Aquaculture and fisheries scientists would no doubt agree unanimously that the well-being of aquatic animals is strongly affected by the condition of the water in which they live. Nevertheless, university-level students of aquaculture and fisheries receive surprisingly little training in water quality and other aspects of water science. Most aquaculture and fisheries students take a course in limnology that provides a general coverage of physical, chemical, and biological processes in lakes. Although they also take courses about aquaculture or fisheries management that touch on selected aspects of water quality in a cursory way, this exposure to water quality hardly serves as a well-rounded introduction to the subject.

Soil rather than water is the milieu for most crop plant production. It is interesting to contrast the curricula in aquaculture and fisheries programs with those in agronomy and soils. Agronomy and soils students are required to take a basic soil science course that usually is quite thorough. They also must take some combination of courses such as soil morphology, soil chemistry, soil physics, soil microbiology, soil fertility and soil conservation.

Auburn University has trained many aquaculture and fisheries students at undergraduate and graduate levels. I had the opportunity at this institution to teach a course focusing on general water quality for upper-level undergraduate and graduate students and to develop and teach a graduate course in aquaculture water quality management. I have taught the general water quality course since 1971 and the other course since 1974. The purpose of this article is to give some suggestions on what should be taught in a general water quality course and to provide some opinions about the status of water quality education for aquaculture and fisheries students.

Suggested Content for a General Water Quality Course

A general course in water quality should provide students an opportunity to learn the fundamental aspects of the subject. The goal is for students to learn enough to understand how major water quality variables effect fish and other aquatic life. The course also should prepare aquaculture students for further study about water quality management.

The contents of the course provided here is offered as a possible guideline to anyone desiring to initiate a course on general water quality for aquaculture and fisheries students. The different course divisions are presented as narrative rather than as an outline. This was done to point out why certain topics should be included. Different water quality variables tend to be strongly interrelated as a change in the concentration of one variable usually is associated with changes in other variables. Moreover, water quality conditions affect biological processes and *vice versa*.

There is no ideal or completely logical starting point, so the order of the class topics can be arranged according to the instructor's preference. The number of 50-min lecture periods devoted to a section is given at the end of each. There are 40 lectures and three additional 50-min periods for tests. Of course, a final examination is given at an assigned time.

Introduction to course. The importance of water in natural ecosystems and for human use is summarized, water quality is defined and the importance of water quality to beneficial uses of water is explained, with particular emphasis on aquaculture and fisheries. A few comments are made related to the urgency for better water conservation and water quality protection as a result of global population growth and looming water shortages in many regions. A 20-min test to assess the general water quality knowledge of students entering the course is given. (2 lectures)

Physical properties of water. Physical properties of water include molecular structure, hydrogen bonding, thermal characteristics, vapor pressure, density, surface phenomena, viscosity, elasticity and compressibility, water pressure, dialectic constant, conductivity, and transparency. Several examples of how these properties influence water's behavior are given, e.g., hydrogen bonding and phase changes, how cohesion and adhesion cause capillarity, the water temperature-density relationship allowing thermal stratification of lakes and ponds, and the effect of high dielectric constant of water on solvent action. (2 lectures)

An overview of hydrology and water supply. This section begins with a presentation on the amounts of water and renewal times of water in the different compartments of the hydrosphere and a description of the hydrological cycle. The world presently has as much water as it ever did and ever will, and the main reasons for water shortages are mentioned. Emphasis is given to the fact that aquaculture facilities should be sited, designed, constructed, and operated in harmony with local hydrologic conditions. Other topics include basic methods of measuring precipitation, evaporation, evapotranspiration, and runoff (including streamflow) and use of hydrological data to make water budgets for watershed ponds, embankment ponds and lakes. The section ends with a brief discussion of world water balance, water availability, the water footprint and global water use. (3 lectures)

Dissolved solids. This section is introduced by identifying the dissolved solids (major anions and cations, trace elements, and dissolved organic matter) and pointing out which dissolved substances are plant nutrients. The distinction between dissolved and suspended matter is made and methods for determining total dissolved solids, salinity, electrical conductivity, the various fractions of the solids, and calculation of charge balance (anion-cation balance) are presented.

It is useful to show data on concentrations of major ions and total dissolved solids from different types of water bodies (streams, lakes, ponds and groundwater aquifers) in regions with different geological characteristics and climatic regimes. These data may be used to illustrate how characteristics of soils and other geological formations, temperature, rainfall, evaporation, contact time between water and minerals and certain characteristics of groundwater interact to govern

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major ion concentrations (and dissolved solids concentrations) in waters from different regions and sources. It is important to contrast the compositions of freshwater, inland saline waters, estuarine waters and normal seawater.

A few other topics are included: effects of total dissolved solids on colligative properties, the sodium absorption ratio, dissolved solids removal and significance of dissolved solids, especially effects on osmoregulation. A few of these topics are not important in aquaculture and fisheries, but students need a broad general overview of the importance of dissolved substances in water. (3 lectures)

Particulate matter, color, turbidity, and light. Particulate matter is suspended in water but, with the exception of colloidal particles, suspended particles tend to settle out. The Stokes' law equation for the velocity of settling particles is presented and the effects of turbulence on settling explained. Color, turbidity and light penetration are defined and then discussed in relation to their effects on primary productivity in water bodies. Methods for measuring turbidity and color are described, and particular emphasis is given to the Secchi disk for assessing turbidity. (1 lecture)

Dissolved oxygen and other gases. The composition of the atmosphere and atmospheric pressure are discussed. Gas solubility in water is explained using oxygen in most of the discussion. This effort requires explanation of Dalton's law of partial pressure, Henry's law constants and Bunsen coefficients. Bunsen coefficients are used to show how a dissolved oxygen solubility table is made. Percentage saturation, oxygen tension, ΔP and gas bubble disease are discussed. Gas transfer between gas and water is illustrated by use of diffusion theory and the practical estimation of mass transfer of gas between air and water is explained. Finally, there is a detailed discussion of the absorption and use of dissolved oxygen by fish, the excretion of carbon dioxide from fish respiration and of effects of concentrations of total gases, dissolved oxygen and carbon dioxide on fish. (4 lectures)

Redox potential. Selected oxidation and reduction reactions are illustrated by balancing electron transfers in equations. Cell voltage and free-energy change are explained using Gibbs free energy of reaction, law of mass action and the equilibrium constant. The hydrogen electrode is described and used to illustrate measurements of standard electrode potentials. The Nernst equation is derived and used to show how redox values change with different concentrations of oxidants and reductants. The necessity of using a calomel electrode (instead of a hydrogen electrode) in practical measurement of redox is explained. The use of redox in predicting whether certain reactions (especially those mediated by microbial processes) will occur is illustrated. While redox is important in many end-point detections in analytical chemistry, in many industrial operations and in explaining reactions and microbial processes, it cannot be easily or accurately measured in most aquaculture systems. It should be stressed that water containing only 1 mg/L of dissolved oxygen will have a high redox potential and aerobic processes will dominate. Finally, the role of redox in corrosion is discussed. (2 lectures)

pH, carbon dioxide, and alkalinity. An understanding of this section is particularly important, but it also is the topic with which most students have the greatest difficulty understanding. A good beginning point is a thorough discussion of the pH concept and the influence of carbon dioxide on pH. The major sources of alkalinity (not limestone alone) should be presented and the determination of alkalinity carefully explained. Students should grasp that alkalinity is the total concentration of titratable bases in water expressed as equivalent calcium carbonate. In reality, alkalinity is an index (like pH) rather than a specific dissolved substance. The expression of alkalinity as equivalent calcium carbonate is particularly confusing to many students. The general concept of buffering can be explained by reference to the acetic acid-sodium acetate buffer system followed by derivation of the Henderson-Hasselbalch equation. The buffering action resulting from the buffer pairs carbon dioxide and bicarbonate (pH $<$ 8.3) and bicarbonate and carbonate (pH $>$ 8.3) should be illustrated by expressing these buffer pairs in the form of the Henderson-Hasselbalch equation.

The carbon dioxide and bicarbonate concentrations are affected by photosynthesis and respiration and usually controls pH in natural waters and aquaculture production systems. This relationship needs to be carefully explained, showing why pH rises as carbon dioxide is removed from water. When pH reaches 8.3, no free carbon dioxide remains, but most aquatic plants can use bicarbonate as a carbon source in photosynthesis. It should be shown how pH continues to rise as photosynthesis proceeds, because when plants remove carbon dioxide from two bicarbonate ions, carbonate is released and hydrolyzes, resulting in an increase in hydroxide ion (and pH). The benefit of calcium in water to precipitate carbonate and moderate pH should be mentioned.

The concept of acidity and the measurement of this variable is discussed. It seems important to indicate that waters with pH values up to 8.3 contains acidity because of the presence of carbon dioxide, while waters with pH values down to around 4.5 contains alkalinity. However, pH below about 4.5 results from acids stronger than carbon dioxide. These generalizations confuse students because they usually think of pH below 7 as acidic and above 7 as alkaline. Finally, the significance of pH and concentrations of carbon dioxide, alkalinity and acidity in aquaculture and fisheries are discussed. (5 lectures)

Total hardness. Total hardness is defined, its sources mentioned, the method of its measurement as equivalent calcium carbonate is described and its concentration range presented. Relationships between total alkalinity and total hardness concentrations in waters from different sources and regions are discussed. The types of hardness (calcium hardness, magnesium hardness, permanent hardness and temporary hardness) are explained. Because of the chemical reactions involved, it is useful to discuss the lime-soda ash process of softening water. Other topics covered are water softening by cation exchange and the calcium-carbonate saturation index. (2 lectures)

Microorganisms and water quality. The activity of phytoplankton and microorganisms of decay (especially bacteria) have a great influence on water quality. The growth pattern of bacteria and the fundamentals of aerobic and anaerobic respiration are presented. Students seem to have the notion that anaerobic respiration involves only fermentation. It is important to explain the different types of anaerobic respiration carried out by chemotrophic bacteria. Sediment respiration should be discussed because it often plays an important role in water quality.

A brief summary of the nature of phytoplankton communities should be provided and the process of photosynthesis reviewed. Graphical illustration of the daily fluctuations of pH and concentrations of carbon dioxide and dissolved oxygen in ponds with different levels of phytoplankton abundance is essential. The nutrient requirements of algae should be discussed, and it is important to stress that nitrogen and phosphorus are most likely to cause excessive phytoplankton growth. There also should be brief discussions of eutrophication and harmful algae.

Chlorination is widely used for disinfection before stocking in hatchery tanks and sometimes in production ponds. This section is the best place to discuss chlorination and possibly other means of disinfection. (4 lectures)

Nitrogen. The global nitrogen cycle provides a starting point for discussion of nitrogen, because most aspects of the global cycle occur on a smaller scale in water bodies. This discussion should touch on atmospheric, biological and industrial nitrogen fixation, nitrate and ammonium use by plants, protein synthesis in plants, mineralization of organic nitrogen and the role of the carbon to nitrogen ratio in the process, nitrification and denitrification.

The forms of nitrogen and their typical concentration ranges should be presented. Ammonia nitrogen exists in water as ammonia (NH_3) and ammonium (NH_4^+) in a pH- and temperature-dependent equilibrium and nitrite also may reach appreciable concentrations. Both ammonia and nitrite can be toxic to fish and shrimp and factors affecting their concentrations in aquaculture systems and the effects of these potential toxins on culture species deserve careful attention.

The role of nitrogen in aquatic plant growth should be emphasized again in this section. Students should be made aware that eutrophication in aquaculture systems is not considered undesirable as it is in natural water bodies. (3 lectures)

Phosphorus. The physicochemical nature of the phosphorus cycle, as opposed to the biological nature of the nitrogen cycle, is a good starting point. The dissociation of orthophosphoric acid may be used to show that plants must use mainly $H_2PO_4^-$ or HPO_4^{2-} and point out that the common use of PO_4 in references to phosphorus concentrations is simply a shorthand for phosphate in general. The production of agricultural phosphates from rock phosphate should be briefly explained. When soluble phosphorus sources are applied to ponds, much of the phosphorus quickly becomes bound in sediment by reactions with clay, iron, aluminum and calcium. These reactions should be explained using the appropriate equations. The student should be led to realize that bottom soils are a sink for phosphorus in aquaculture ponds and the release of phosphorus from bottom soil usually will not be adequate to cause high phytoplankton abundance. The exchange of phosphorus under aerobic and anaerobic conditions at the sediment-water interface is important to include. The role of phosphorus in eutrophication of natural waters is important but again students should learn that aquaculture systems are intentionally enriched. (2 lectures)

Sulfur. This section should be included because sulfide is a potential toxin in aquaculture and ponds are sometimes built in acid-sulfate soils resulting in highly acidic water. Sulfate also is a nutrient but its concentration seldom limits productivity in natural water bodies or aquaculture systems. Topics that should be covered in this section are the global sulfur cycle, sulfur oxidations and reductions, hydrogen sulfide toxicity, typical forms and concentrations of sulfur in water, acid-sulfate soils and acid-mine drainage. (1 lecture)

Micronutrients and other trace elements. The section can begin with a general discussion of the micronutrients and their importance in plant and animal nutrition. Micronutrients required only by plants, only by animals and by both plants and animals should be identified. Students should learn that trace element concentrations in water depend on the solubility and abundance of controlling minerals, pH, redox, temperature and formation of ion pairs and complex ions. The free ionic concentrations of trace metals is typically lower than the amount present in ion pairs and complexes. The free ionic form of trace metals are the forms absorbed by plants and the ion pairs and complexes are in equilibrium with the free ionic form. The effects of ion pairs and complexes on both availability and toxicity of trace metals should be discussed.

Aluminum is not a nutrient, but its chemistry should be discussed, and the other non-nutritive trace elements that may be toxic under some conditions should be mentioned.

It is useful to mention the concentration ranges for the more important trace elements found in water and to indicate the maximum concentration usually considered acceptable for each element. The use of toxicity tests to establish acceptable concentrations of potentially toxic substances in aquaculture is discussed here, but it could be discussed earlier if desired. (3 lectures)

Water pollution in aquaculture. Water pollution is discussed in general with reference to types of pollution, water quality standards and government water pollution regulations. Methods for assessing fish kills in water bodies are outlined. Attention also is given to the negative environmental impacts of aquaculture. Aquaculture effluents contain pollutants because inorganic and organic nutrients added to culture systems in fertilizers and feeds are only partially converted to the biomass of culture species. The substance most likely to cause water pollution are suspended solids, nitrogen and phosphorus. A material budget for carbon, nitrogen and phosphorus in feed can be used to illustrate that only around 20-40 percent of nitrogen and phosphorus and 10-15 percent of the organic carbon in feed is converted to biomass. The remainder of these elements enter culture systems, where natural processes may remove considerable amounts, especially in ponds. Nevertheless, effluents contain potential pollutants and aquaculture facilities may be required to comply with effluent concentration or load limits. (3 lectures)

Simple Explanations of Processes

Interactions among water quality variables and biological activity often are complex and typically involve biochemical pathways and physiological processes. Nevertheless, it is necessary for the water quality student to grasp certain aspects of these processes, and simple diagrams often can be greatly beneficial.

Aquatic plants use carbon dioxide in photosynthesis but, when pH exceeds 8.3, there is no free carbon dioxide. Photosynthesis does not stop because most aquatic plants can use bicarbonate as a source of inorganic carbon. The removal of carbon dioxide from bicarbonate by the carbonic anhydrase pathway releases carbonate. Carbonate hydrolyses increases the hydroxide concentration and pH continues to rise. But calcium in the water reacts with carbonate leading to calcium carbonate precipitation and this moderates the pH increase. At night, carbon dioxide from respiration enters the water to reverse the process. The diagram (Fig. 1) illustrates this phenomenon.

The significance of processes such as photosynthesis, nutrient uptake by plants, conversion of photosynthetic to plant biomass, trophic transfers, aerobic respiration, excretion of metabolic waste by culture animals, nitrification and anaerobic respiration can be explained without delving too deeply into physiology. For example, a simple diagram such as Figure 2 can be used to explain the basic

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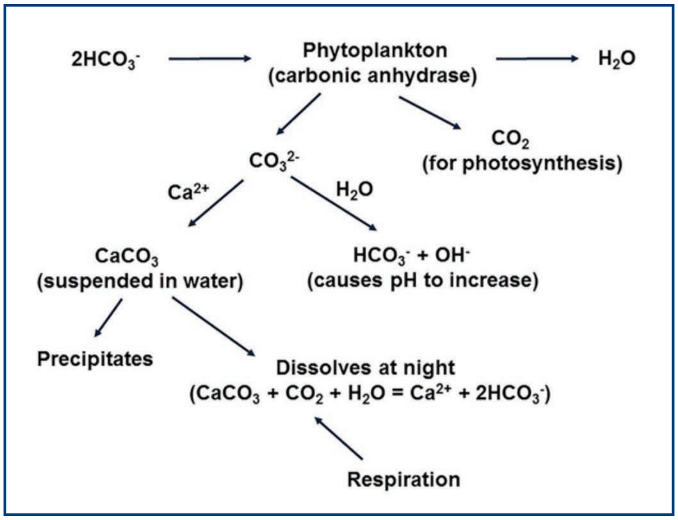

FIGURE 1. *Use of bicarbonate by aquatic plants as an inorganic carbon source for photosynthesis in absence of free carbon dioxide (above pH 8.3).*

features of photosynthesis. Plant pigments capture photons of light and use this energy to lyse water and provide electrons and hydrogen ions for the reduction of carbon dioxide to carbohydrate $(CH_2O)_n$. Energy captured by photosynthetic pigments also is transferred to ATP in a process called photophosphorylation and the energy trapped in ATP is transferred to carbohydrate when carbon dioxide is reduced to organic carbon.

Despite being quite different physiological processes, photosynthesis and respiration can, for ecological purposes, be considered the reverse of each other.

$$6CO_2 + 6H_2O + \text{energy} + \text{minerals} \underset{\text{respiration}}{\overset{\text{photosynthesis}}{\longleftrightarrow}} C_6H_{12}O_6 + 6O_2$$

Photosynthesis requires light energy and minerals, removes carbon dioxide and releases oxygen, and reduces inorganic carbon to organic carbon. Respiration does not require light and minerals and it releases energy, it uses oxygen and releases carbon dioxide, and it oxidizes organic carbon to inorganic carbon. Dissolved oxygen concentration tends to be high and carbon dioxide concentration low when photosynthesis is proceeding faster than respiration, and *vice versa*.

Aerobic respiration can be explained without going through a detailed biochemical explanation of glycolysis and the Krebs cycle,

Basic, summary equations:

$\text{Organic C} + O_2 \rightarrow CO_2 + \text{energy} \rightarrow \text{Heat (to environment)}$

$ADP + PO_4 + \text{energy} \leftrightarrow \text{ATP (energy for cellular work)}$

Stoichiometry:

$$\underset{12}{\overset{1\text{ gram}}{\text{Organic C}}} + \underset{32}{\overset{x}{O_2}} \rightarrow CO_2$$

$x = 2.67$ g O_2/g organic C oxidized.

TABLE 1. *Simplification of aerobic respiration and stoichiometry of organic carbon oxidized to molecular oxygen used.*

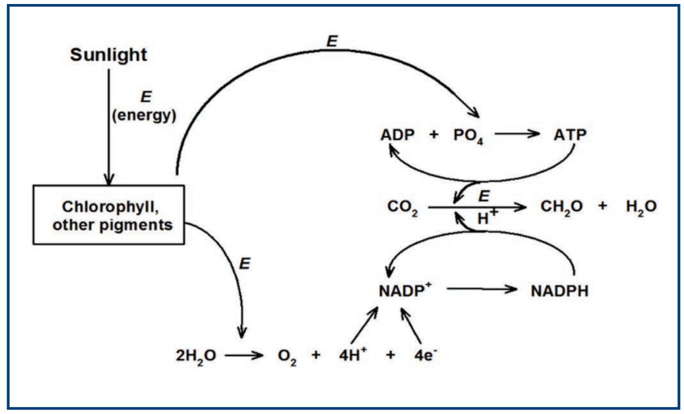

FIGURE 2. *Illustration of the basic reactions occurring in photosynthesis.*

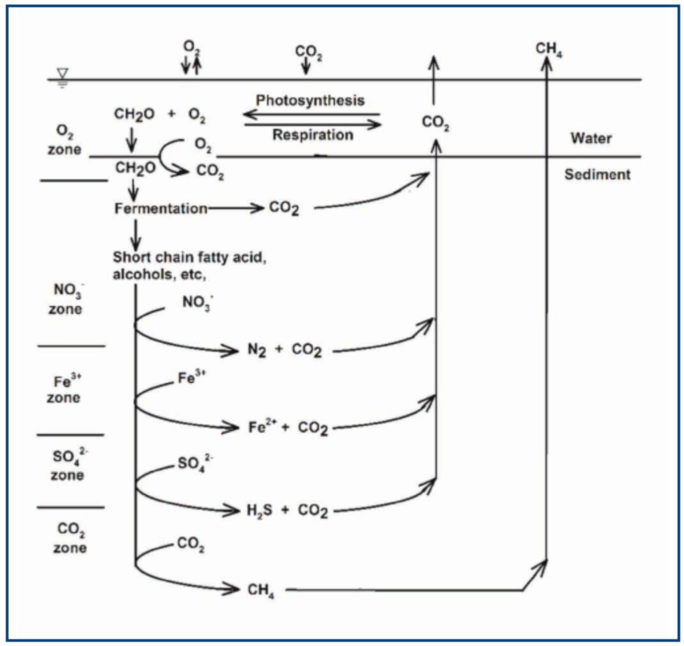

FIGURE 3. *Zonation of water and sediment based on electron acceptors in respiration.*

although these processes should be referred to. The simple explanation in Table 1 can be used to illustrate oxygen use in aerobic respiration.

Anaerobic respiration may be explained with simple summary equations such as the one for oxidation of acetic acid by iron reducing bacteria. It is helpful to explain the role of the redox potential in the sequence of the various possible microbial processes, and to illustrate the way that the reactions tend to be stratified with sediment depth (Fig. 3). Simple explanations of significance of most biological processes on water quality are possible. Those teaching water science should use their ingenuity to prepare diagrams to explain the basic features of processes involved in controlling concentrations of water quality variables.

Background of Students

The general water quality course requires the use of principles and concepts from physics and chemistry as well as the application of mathematics, especially algebra. Many students who enter the water science course have taken only basic chemistry (introductory inorganic and sometimes introductory organic chemistry), introductory physics, but most have taken at least pre-calculus and some have taken calculus. Handouts with background information on chemistry and physics useful in the class are provided for independent study by the students, and one or more graduate students (who are studying aquaculture water quality) teach a review session weekly.

The students typically enter the water quality course with the belief that they have at least a "talking knowledge" of the subject. I give a basic, preliminary test (see text box) to ascertain their water quality knowledge. The best score ever on this test was nine correct out of 20 questions. I have provided the answers to the test for reference by any readers willing to assess their general water quality knowledge.

Memorization of important factors about a subject is desirable, but memorization does not assure an ability to use facts and principles to reach logical answers to questions or to solve problems. Therefore, tests in the course are "open book" and students must use information presented in the lectures to arrive at solutions to test questions. Calculations are necessary for answering about half of the questions. Because test questions cannot be answered by recalling lecture information from memory, many students do poorly on the first test despite having been advised that logic and problem solving will be required.

The course has always been attended by a mixture of 30-40 percent undergraduates and 60-70 percent graduate students and, as would be expected, most graduate students make higher scores than most undergraduates, and scores are ranked separately. Many international graduate students have studied aquaculture at Auburn University, and a large percentage of them took the general water quality class.

Declining Enrollment of Students in Water Science

A total of 1,341 fisheries and aquaculture students took the Water Science class at Auburn University between 1972 and 2017. This number is approximately 80 percent of the fisheries and aquaculture graduates over that 46-yr period. However, enrollment has been declining, for reasons that are unclear.

The emphasis today is on "cutting-edge" science (whatever that is supposed to mean) and "novel" science (that seems even harder to define) that is published in "high impact" journals. Water science and water quality are neither "cutting-edge" nor "novel" courses.

Graduate programs typically do not have specific course requirements, and courses are selected according to the desires of the student, the major professor and graduate committee members. Researchers on graduate committees have become very specialized, reflecting the current trend in science. Thus, many committees overlook the importance of fisheries and aquaculture students taking courses related to water quality and environmental management. The upshot is that there appears to be a declining interest in teaching water quality and environmental topics in aquaculture.

Note

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General Water Quality Knowledge Assessment

1. Which water quality variable is defined as the total concentration of bases expressed as equivalent $CaCO_3$?
2. Which water quality variable is defined as the total concentration of divalent cations expressed as equivalent $CaCO_3$?
3. What is the numerical value of the dissociation constant of water (K_w; $H_2O = H^+ + OH^-$) at 25°C?
4. Above what pH does water not contain free carbon dioxide?
5. What is the average salinity of seawater in milligrams per liter?
6. What is the percentage saturation of molecular oxygen in water at equilibrium with atmospheric air?
7. At what temperature does 1 m^3 of freshwater weigh 1.0000 metric ton (tonne)?
8. Name the biological process in which ammonia is oxidized to nitrate.
9. Estimate the weight in kilograms of residue remaining after evaporation of 1 m^3 of water that contains 1 part per thousand (ppt) of total dissolved solids.
10. List the pH above which freshwater may contain measurable carbonate (CO_3^{2-}).
11. What is the approximate dissolved oxygen concentration at saturation (in milligrams per liter) for freshwater at mean sea level and at 20°C?
12. Humic substances in water ___________________________ trace metals.
13. List a major cation found in natural water:
14. List a major anion found in natural water:
15. 1 mg/L NO_3-N contains a. more, b. less, c. same amount of nitrogen as 1 mg/L NO_3.
16. Name one of the two nutrients most commonly associated with eutrophication:
17. In aerobic respiration, how many grams of molecular oxygen are necessary to completely oxidize 1.00 g of organic carbon?
18. What is the numerical value of the factor relating the total amount of organic carbon produced in photosynthesis to the total amount of oxygen released?
19. What is the pH below which water is often said to contain mineral acidity?
20. Aluminum ion ____________________________________ in water releasing H^+.

Answers in order: total alkalinity; total hardness; 10^{-14}; 8.3; 34,500; 100 percent; »4°C; nitrification; 1.0; 8.3; 9.08; chelate Ca, Mg, K. or Na acceptable; SO_4, Cl, HCO_3^- acceptable; more; nitrogen or phosphorus; 2.67; 0.375 (12/32); 4.5; hydrolyzes.