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# THEORY AND PRACTICE OF WATER AND WASTEWATER TREATMENT

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# PREFACE

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This book has been written as an undergraduate text based on the typical background of a civil engineering student. Necessary background information for design and assessment of treatment processes is included in the first sections. These sections do include some review of basic concepts from other courses and should not be considered as replacing the need for these courses. However, these concepts have been focused upon the needs of the water quality environmental engineer.

Basic theory of most treatment processes is presented in later sections. The variety of treatment processes is increasing and the issues surrounding their application are more subtle. An introductory coverage of most of the processes is given with more emphasis on common applications. Processes are grouped according to theoretical principles rather than their occurrence in water or wastewater treatment operations. It has been the experience of the author that many books on the subject simply present formulae without any detailed development. This book addresses that problem. The reader is made aware of theoretical and empirical developments. In addition to text references, key references are provided for consultation by the student who wishes to examine a topic in more detail or consult another presentation on the topic.

This book has a more intense focus on the mechanics of the processes used to treat water or wastewater. For instance, design of water distribution and wastewater collection systems are applied hydraulics exercises that are left to other courses. The theory presented in this book is at the level of an undergraduate. In the past much of this basic theory was left for the graduate level. As need and room in the undergraduate curriculum for environmental engineering grows, the opportunity now exists to bring undergraduates to a level of theoretical comprehension equivalent to that gained in other disciplines.

The material in this book includes substantial portions of three undergraduate courses given at the University of Ottawa. The first course covers Chapters 1–9, Sections 15.1–15.4, Chapter 16, and Chapter 21. This course is accompanied by weekly laboratory exercises. The second course covers Chapters 10–15 and a few introductory sections from Chapter 17. The remaining material is covered in an elective course with additional material. The extent of topic coverage in each course has changed as the environmental engineering curriculum and support courses have evolved. The material in the book can be organized in numerous ways depending on the backgrounds of students and the breadth and depth of the environmental engineering curriculum.

As a note to the reader, the theory presented is the first principles for design and operation of treatment processes. These principles govern the major phenomena occurring in a process but, as with all models, they are idealizations. Field studies are always required to confirm or refine the basic theory results into processes that will meet the objectives. Typical design ranges are given for most processes. There is a growing body of design handbooks available that note many practical considerations and experiences for consideration in design and process analysis. At the end of each chapter key references are supplied for the readers who wish to expand their coverage of the topics in the chapter.

Advanced study will yield understanding of missing components in some models and modify results obtained from basic models to results closer to those used in

practice. But understanding the basic theory has often been the reason for significant advancements in the field. The development of tube and lamella clarifiers and new configurations for anaerobic biological wastewater treatment are two instances in which understanding and application of basic concepts for the former have resulted in detention time reductions of 50% or more and, in the latter, reductions by a factor of 10 or more.

## Abbreviations and Acronyms Used in the Text

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ABES—Associação Brasileira de Engenharia Sanitária e Ambiental	EC <sub>50</sub> —see LC <sub>50</sub>
Acy—acidity	EDTA—ethylene-diamine-tetraacetic acid
acu—apparent color unit	EMF—electromotive force
ADP—adenosine diphosphate	EPA—Environmental Protection Agency
AIDS—acquired immunodeficiency syndrome	eq—equivalent
Alk—alkalinity	ES—effective size
A/O—anaerobic/oxic	FAO—Food and Agriculture Organization
AMP—adenosine monophosphate	FC—fecal coliforms
APHA—American Public Health Association	FD—filtration and disinfection
aq—aqueous	FE—free energy
ASCE—American Society of Civil Engineers	F:M—food: microorganism ratio
ASME—American Society of Mechanical Engineers	Fr—Froude number
asu—areal standard unit	FS—fecal streptococci
ATA—anaerobic toxicity assay	FSS—fixed suspended solids
atm—atmosphere	ft—foot (feet)
ATP—adenosine triphosphate	g—gaseous; gram
AWWA—American Water Works Association	GAC—granular activated carbon
BAT—best available technology	gal—gallon (U.S.)
BDST—bed-depth-service time	GLUMRB—Great Lakes Upper Mississippi River Board
BMP—biomethane potential	GTP—guanosine triphosphate
BOD—biochemical oxygen demand	HIV—human immunodeficiency viruses
BOD <sub>u</sub> —ultimate BOD	h—hour
bp—boiling point	ha—hectare
Bq—Becquerel	hp—horsepower
Btu—British thermal unit	HPC—heterotrophic plate count
cap—capita	HRT—hydraulic retention time
c/c—center to center	IAWPRC—International Association on Water Pollution Research and Control
CCME—Canadian Council of Ministers of the Environment	IAWQ—International Association on Water Quality
CFU—colony forming unit	i.d.—internal diameter
CH—carbonate hardness	IJC—International Joint Commission
Ci—curie	IMAC—interim maximum acceptable concentration
CM—complete mixed	in.—inch
COD—chemical oxygen demand	IRC—International Reference Centre
CSCE—Canadian Society of Civil Engineers	ISS—inert suspended solids
CSTR—completely stirred tank reactor	IUPAC—International Union of Pure and Applied Chemistry
1-D—one-dimensional	L—length; liter
DC—direct current	l—liquid
DDT—dichloro-diphenyl-trichloroethane	lb—pound
deg—degree	LC <sub>50</sub> —lethal concentration for 50% of the organisms
DF—dilution factor	LHS—left-hand side
DNA—deoxyribonucleic acid	LI—Langelier index
DO—dissolved oxygen	ln—natural (base <i>e</i> ) or Napierian logarithm
DPD— <i>N,N</i> -diethyl- <i>p</i> -phenylenediamine	log—base 10 logarithm
DSFF—downflow stationary fixed film	<i>m</i> —molal; meter
DST—defined substrate technology	M—mass
EBCT—empty bed contact time	<i>M</i> —molar
	MAC—maximum acceptable concentration

## Abbreviations and Acronyms Used in the Text (continued)

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MAF—Ministry of Agriculture and Food	rms—root mean square
MCL—maximum contaminant level	RO—reverse osmosis
MCLG—maximum contaminant level goal	rpm—revolutions per minute
MF—membrane filter	s—solid; second(s)
Mgal/d—million gallons (U.S.) per day	SBR—sequencing batch reactor
min—minute	SDWA—Safe Drinking Water Act
ML—mixed liquor	s.g.—specific gravity
MLVSS—mixed liquor volatile suspended solids	SHE—standard hydrogen electrode
MLTSS—mixed liquor total suspended solids	SI—Système International; saturation index
mo.—month	SOC—synthetic organic chemical
MOE—Ministry of the Environment	SR—slow rate land treatment
mp—melting point	SRT—solids retention time
MPN—most probable number	SS—suspended solids
MUG—methylumbelliferyl- $\beta$ - <i>D</i> -glucuronide	STP—standard temperature and pressure
MW—molecular weight	Sv—sievert
N—Newton	SVI—sludge volume index
<i>N</i> —normal	SWTR—Surface Water Treatment Rule
NAD—nicotinamide adenine dinucleotide	T—time
NADP—nicotinamide adenine dinucleotide phosphate	TBOD—total biochemical oxygen demand
NCH—noncarbonate hardness	TC—total coliforms
ND—nondetectable	TCA—tricarboxylic acid
NOD—nitrogenous oxygen demand	TDS—total dissolved solids
NOEC—no observed effect concentration	TH—total hardness
NTA—nitroloacetic acid	THM—trihalomethane
NTU—nephelometric turbidity unit	TKN—total Kjeldahl nitrogen
o.d.—outside diameter	TNTC—too numerous to count
OF—overland flow land treatment	TOC—total organic carbon
OI—odor index	TON—threshold odor number
ONPG— <i>o</i> -nitrophenol- $\beta$ - <i>D</i> -galactopyranoside	TOX—total organic halides
ORP—oxidation–reduction potential	TSS—total suspended solids
OUR—oxygen uptake rate	TU—turbidity unit
P/A—presence–absence	TVA—Tennessee Valley Authority
PAC—powdered activated carbon	UASB—upflow anaerobic sludge blanket
PACT—powdered activated carbon activated sludge process	U.K.—United Kingdom
PF—plug flow	UNICEF—United Nations International Children's Emergency Fund
PFU—plaque forming unit	U.S.—United States
PHB—poly- $\beta$ -hydroxybutyric acid	USEPA—United States Environmental Protection Agency
psi—pounds per square inch	UV—ultraviolet
PVC—polyvinylchloride	VOC—volatile organic chemical
rad—roentgen absorption dose	VS—volatile solids
Re—Reynold's number	VSS—volatile suspended solids
redox—oxidation–reduction	W—watt
rem—roentgen-equivalent-man	WAS—waste activated sludge
rev—revolution	WEF—Water Environment Federation
RHS—right-hand side	WHO—World Health Organization
RI—rapid infiltration land treatment	wk—week
	WPCF—Water Pollution Control Federation
	yr—year

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SECTION I

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**CHEMISTRY**



## BASIC CHEMISTRY

This chapter gives a review of chemistry definitions and fundamentals to refresh and supplement background obtained in first courses. Our view is toward the applied chemistry of water and wastewater and their treatment.

### 1.1 DEFINITIONS

A fundamental substance that cannot be further decomposed by ordinary chemical means is an element. The smallest unit of an element is an atom. The names, symbols, atomic numbers, and atomic weights of the elements are provided for convenience in a periodic chart and a table located inside the front and back covers, respectively, of the book. The symbols are not always the first letter(s) of the element names because they are derived from the Latin, Greek, or German names of the elements.

The atomic number is the number of protons in the atom, whereas the atomic weight reflects the number of protons and neutrons contained in the atom. Atoms with the same number of protons but different atomic weights are isotopes of an element. Atomic weights of the elements are referred to the weight of the  $^{12}\text{C}$  isotope of carbon, which was assigned a value of exactly 12 by the International Union of Pure and Applied Chemistry (IUPAC).<sup>1</sup> The atomic weight also reflects the relative occurrence of isotopes of a given element. Isotopes contain the same number of protons, and therefore electrons, but differ in the number of neutrons. The precision of the atomic weight depends upon the natural variation in occurrence of the isotopes. The atomic weights are all constant within three significant digits, which is suitable for engineering calculations.

The gram atomic weight refers to the quantity of an element in grams equal to the atomic weight of the element. One gram atomic weight of an element or compound contains one Avogadro number ( $6.023 \times 10^{23}$ ) of each of the atoms contained in the chemical formula. The gram molecular weight refers to the molecular weight (MW) of a compound in grams.

### 1.2 THE EXPRESSION OF CONCENTRATION

Concentration of ions in a solution is expressed on the following bases: molar, molal, mole fraction, or mass concentration.

**Molar.** Molar concentration is the number of moles per volume of solution indicated by  $M$ . A 1  $M$  solution contains one mole per liter.

<sup>1</sup>Abbreviations and acronyms used in the text are defined after the preface.

**Molal.** Molal concentration expresses the number of moles per 1 000 g of solvent (water). A molal concentration is indicated by  $m$ . Density and volume of a solution are influenced by the characteristics and quantities of dissolved substances and the temperature of the solution; thus the volume of 1 000 g of water containing dissolved or suspended substances will not exactly occupy 1 L. (Also there was a slight error in the density determination of pure water.) However, these differences are insignificant and molar and molal concentrations are practically equal for water solutions of interest to environmental engineers.

**Mole Fraction.** The equation defining the mole fraction  $x_i$  of the  $i$ th substance is

$$x_i = \frac{n_i}{\sum n_i}$$

where

$n$  is the number of moles

the denominator is the total number of moles of all substances, including the solvent, in the solution (for  $k$  substances,  $j = 1$  to  $k$ )

Expression of concentration on a mole fraction basis is most useful for thermodynamic analysis.

**Mass Concentration.** Concentration is often expressed in terms of parts per million (ppm) or mg/L. Sometimes parts per thousand (ppt) or parts per billion (ppb) are also used. The concentration of solute X in solvent Y in ppm is

$$\text{ppm} = \frac{\text{mass of substance}}{\text{mass of solution}} \quad \text{e.g.,} \quad \frac{x \text{ g of X}}{10^6 \text{ g of (Y + X)}} = x \text{ ppm}$$

Because 1 kg of solution with water as a solvent has a volume of approximately 1 liter,

$$1 \text{ ppm} \approx 1 \text{ mg/L}$$

Square brackets, [ ], around a species indicate concentration of the species (e.g.,  $[\text{Cl}_2]$  indicates concentration of  $\text{Cl}_2$ ). The concentration may be expressed in any of the above forms in an equation. The reader is cautioned to take note of the definition of concentration used in each equation.

Tables 1.1, 1.2, and 1.3, given later in this chapter, list various substances found in water. Many important elements exist in various combinations with other elements as discussed in the following sections. The concentrations of many compounds are often reported in terms of the key element in the compound. This is indicated by writing the chemical formula for the compound hyphen (-) the key element. For instance, the concentration of ammonia ( $\text{NH}_3$ ) can be written as  $[\text{NH}_3]$  or  $[\text{NH}_3\text{-N}]$ . The former indicates the concentration of ammonia as ammonia and the latter indicates the concentration of ammonia as nitrogen. The -N is also written "as N," i.e.,  $[\text{NH}_3 \text{ as N}]$ . The transformation between the two concentration expressions is based on the gram molecular weight of the entity and the gram atomic weight of the element. For ammonia the gram molecular weight is 17 g and the gram atomic weight of nitrogen is 14 g. Therefore, 1 mg/L of  $\text{NH}_3$  is equivalent to 14/17 mg/L or 0.82 mg/L of  $\text{NH}_3\text{-N}$  and vice versa. If only the chemical formula is indicated then the concentration is taken as being of the entity itself.

Sometimes the concentration of one species is expressed in terms of another chemical entity based on chemical reactions. Expressing the concentration in terms



of one element or entity is convenient when the element is undergoing transformation from one species to another or when many substances have the same chemical effects.

### ■ Example 1.1 Expression of Concentration

A water contains 3.10 mg/L of  $\text{H}_2\text{S}$ , 1.40 mg/L of  $\text{HS}^-$ , and 26.50 mg/L of  $\text{SO}_4^{2-}$ . Express the concentrations of each species as S and as  $\text{SO}_4^{2-}$ . Base the  $\text{SO}_4^{2-}$  equivalency on the number of sulfur atoms in the entity. The elemental weight<sup>2</sup> of sulfur is 32.1 and the gram molecular weight of  $\text{SO}_4^{2-}$  is 96.1. The table below expresses the concentrations in the various forms.

Substance	[ ], mg/L	As S		As $\text{SO}_4^{2-}$	
		Factor <sup>a</sup>	[ ], mg/L	Factor <sup>a</sup>	[ ], mg/L
$\text{H}_2\text{S}$	3.10	32.1/34.1	$\text{H}_2\text{S-S}$ 2.92	96.1/34.1	$\text{H}_2\text{S-SO}_4^{2-}$ 8.74
$\text{HS}^-$	1.40	32.1/33.1	$\text{HS}^-\text{-S}$ 1.36	96.1/33.1	$\text{HS}^-\text{-SO}_4^{2-}$ 4.06
$\text{SO}_4^{2-}$	26.50	32.1/96.1	$\text{SO}_4^{2-}\text{-S}$ 8.85	96.1/96.1	$\text{SO}_4^{2-}\text{-SO}_4^{2-}$ 26.50
		Total	13.13	Total	39.30

<sup>a</sup> The factors are related to the actual entity.

As indicated in the table the total concentrations of all species as S or  $\text{SO}_4^{2-}$  are 13.13 and 39.30 mg/L, respectively.

## 1.3 IONS, MOLECULES, AND BONDING

Molecules are groups of atoms bonded together. Some atoms or groups of atoms (radicals) are able to completely give up or acquire one or more electrons. This results in a net charge on the species and allows it to bond electrostatically to an oppositely charged species. Charged species are called ions. The valence of an ion is equal to the number of electrons that the atom or group of atoms has lost or gained (see Table 1.1 for examples). In a solution, an ionic compound separates into its component ions. As more compound is added this continues to occur until the solution becomes saturated with the ions and precipitation (formation of a distinct solid phase) of the ionic compound occurs.

Whether a radical or compound actually exists is often a topic for advanced chemistry. Refer to Tables 1.1 and 1.2 and other tables throughout this book, which list information on common elements, radicals, and compounds of concern to environmental engineers.

The other major type of bond is a covalent bond, in which electrons are shared among atoms as opposed to being transferred between them. Covalent bonds are generally stronger than ionic bonds. Atoms forming a radical, which exhibits ionic behavior in solution (has a charge on the entity), are covalently bonded. In covalent bonds between like atoms such as  $\text{Cl}_2$ , and  $\text{O}_2$ , the electrons are equally shared. But when different atoms are covalently bonded, one atom may more strongly attract the electrons than the other, causing a negative charge distribution that is different from

<sup>2</sup>The atomic weights of all elements are given inside the front cover of the book. The periodic table of the elements is given inside the front cover of the book.