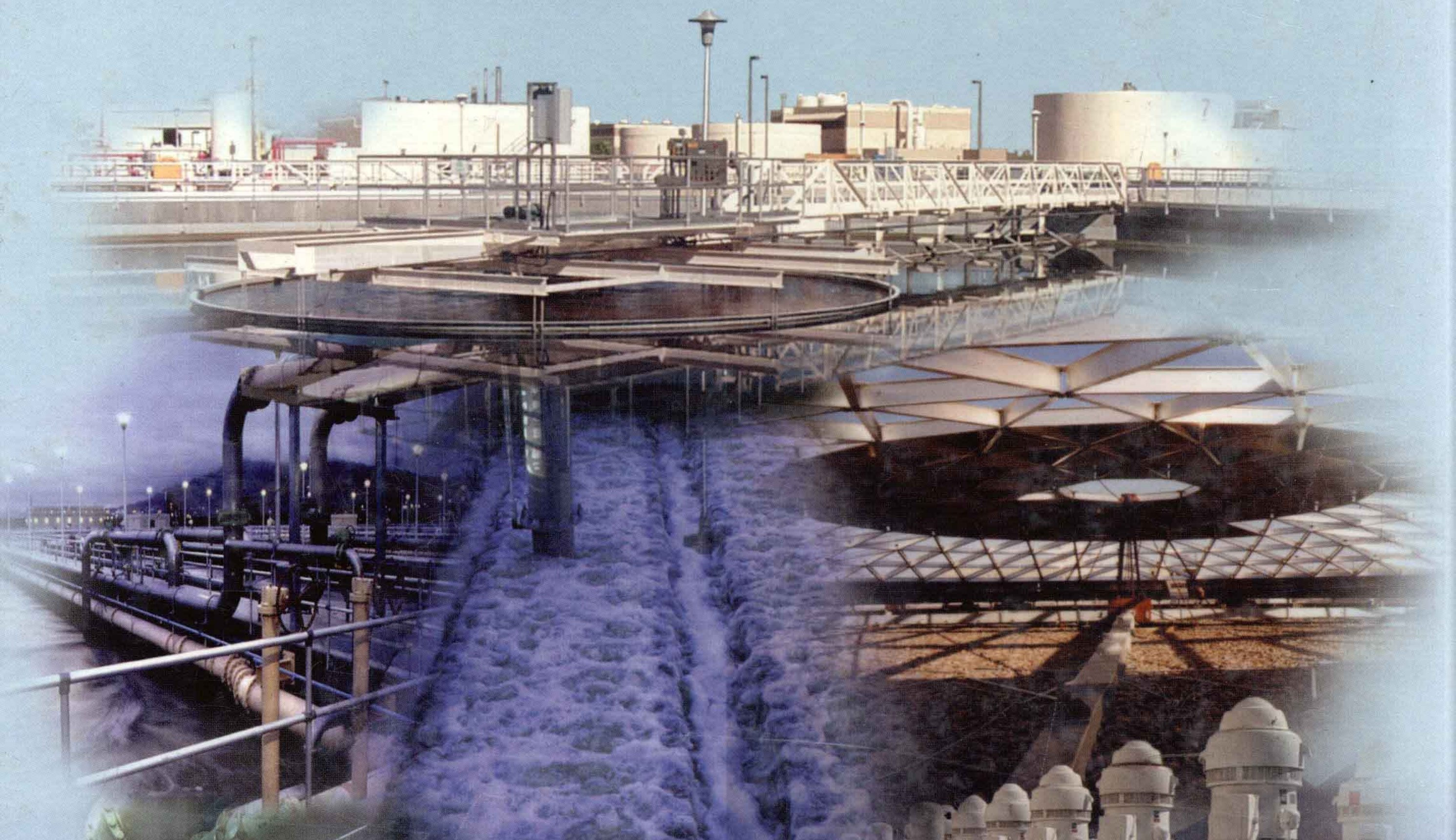
Water and Wastewater Technology

FOURTH EDITION



Mark J. Hammer   Mark J. Hammer, Jr.

Water and Wastewater Technology

Fourth Edition

Mark J. Hammer
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Prentice Hall

Upper Saddle River, New Jersey
Columbus, Ohio

To our mother and grandmother,
Bertha Grundahl Hammer,
and in memory of our father and grandfather,
Herbert Hammer

Library of Congress Cataloging-in-Publication Data
Hammer, Mark J.
Water and wastewater technology / Mark J. Hammer, Mark J. Hammer, Jr.—4th ed.
p. cm.
Includes index.
ISBN 0-13-025867-9
1. Water-supply engineering. 2. Sewage disposal. I. Hammer, Mark J. II. Title.
TD345 .H25 2001
628.1—dc21 00-055762
CIP

Vice President and Publisher: Dave Garza
Editor in Chief: Stephen Helba
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Cover Designer: Ceri Fitzgerald
Cover photos: Courtesy of Mark J. Hammer, Jr.
Production Manager: Matthew Ottenweller
Marketing Manager: Jamie Van Voorhis

This book was set in Trump Mediaeval by York Graphic Services, Inc., and was printed and bound by Courier Kendallville, Inc. The cover was printed by Phoenix Color Corp.

Prentice Hall

10 9 8 7 6 5 4 3
ISBN 0-13-025867-9

Preface

This book provides comprehensive coverage of the fundamental principles and current practices in water processing, water distribution, wastewater collection, wastewater treatment, and sludge processing. The objective is to transfer knowledge of these subjects to persons interested in continuing their study in sanitary technology and engineering, and to persons interested in operation and maintenance of water and wastewater facilities.

This fourth edition updates the subject matter, illustrations, and problems to incorporate new concepts and issues related to the water environment. The most extensive revisions in this edition are the addition of new problems, hydraulics, disinfection of drinking water, wastewater processing, and editing of the previous text.

Based on our experience in education, we believe students benefit from a review of the disciplines that have specific applications in water supply and wastewater management. Therefore, the introductory chapters cover fundamentals of chemistry, biology, hydraulics, and hydrology applicable to sanitary studies. The subjects of water quality and pollution are also introductory to understand the reasons for the selection of processes in water and wastewater treatment.

In presenting water supply and wastewater management, the approach is traditional, with water distribution, processing, and operation of systems separated from wastewater collection, treatment, and operation. We have carefully integrated the subject matter in each area so readers can clearly understand the interrelationships between individual unit operations and integration of systems as a whole. The final chapters on advanced wastewater treatment and water reuse are increasingly important in many regions for pollution control and beneficial use of water resources.

Extensive use of illustrations increases the understanding of concepts and shows modern equipment and facilities. Also, numerous sample calculations assist the reader in the application of equations, charts, and tabulated data. Answers are given for some of the homework problems, mainly to help persons interested in individual study.

A discussion of the book's contents is given in Chapter 1, Introduction.

We would like to thank the reviewers of this edition for their helpful comments and suggestions: Roger Hlavek, Indiana University; Francis J. Hopcroft, Wentworth Institute of Technology; and Jerry A. Nathanson, Union County College.

We hope this book will be of benefit to both present and future colleagues who teach, study, and practice in the area of the water environment.

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Contents

Chapter 1

Introduction

The hydrologic cycle describes the movement of water in nature. Evaporation from the ocean is carried over land areas by maritime air masses. Vapor from inland waters and transpiration from plants add to atmospheric moisture that eventually precipitates as rain or snow. Rainfall may percolate into the ground, join surface watercourses, be taken up by plants, or reevaporate. Groundwater and surface flows drain toward the ocean for recycling.

Humans intervene in the hydrologic cycle, generating artificial water cycles (Figure 1–1). Some communities withdraw groundwater for public supply, but the majority rely on surface sources. After processing, water is distributed to households and industries. Wastewater is collected in a sewer system and transported to a plant for treatment prior to disposal. Conventional methods provide only partial recovery of the original water quality. Dilution into a surface watercourse and purification by nature yield additional quality improvement. However, the next city downstream is likely to withdraw the water for a municipal supply before complete rejuvenation. This city in turn treats and disposes of its wastewater by dilution. This process of withdrawal and return by successive municipalities in a river basin results in indirect water reuse.

During dry weather, maintaining minimum flow in many small rivers relies on the return of upstream wastewater discharges. Thus, an artificial water cycle within the natural hydrologic scheme involves (1) surface-water withdrawal, processing, and distribution; (2) wastewater collection, treatment, and disposal back to surface water by dilution; (3) natural purification in a river; and (4) repetition of this scheme by cities downstream.

Discharge of conventionally treated wastewaters to lakes, reservoirs, and estuaries, which act like lakes, accelerates eutrophication. The resulting deterioration of water quality interferes with indirect

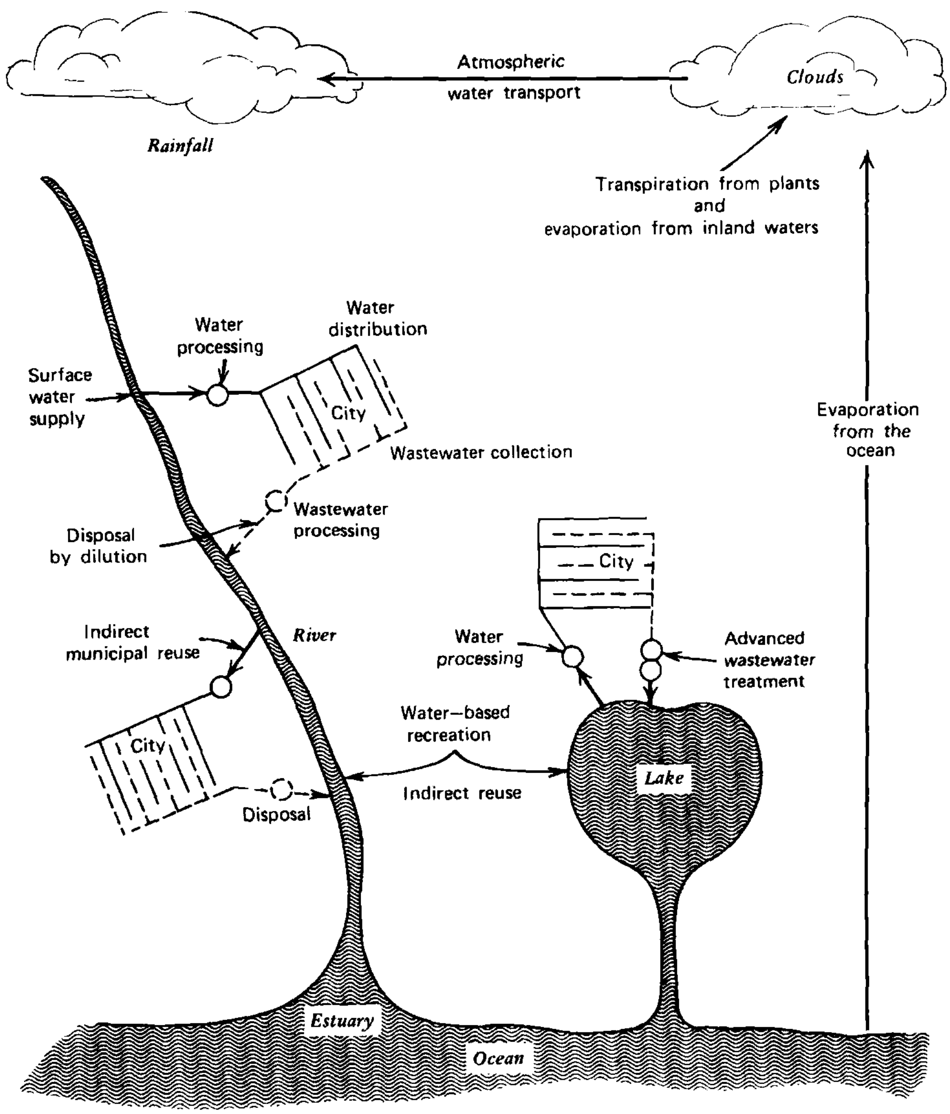

Figure 1–1
Integration of natural and human-generated water cycles.

reuse for public supply and water-based recreational activities. Consequently, advanced wastewater treatment by either mechanical plants or land disposal techniques has been introduced into the artificial water cycle, involving inland lakes and reservoirs.

Installation of advanced treatment systems that reclaim wastewater to nearly its original quality has encouraged several cities to consider direct reuse of water for industrial processing, recreational lakes, irrigation, groundwater recharge, and other applications. However, direct return for a potable water supply is not being encouraged because of potential health hazards from viruses and traces of toxic substances that are difficult to detect and may not be removed in water reclamation. Another problem is the buildup of dissolved salts that can be removed only by costly demineralization processes. Nevertheless, with the increase in demand for fresh water, direct water reuse by some metropolitan areas may be realistic in the future.

The basic sciences of chemistry, biology, hydraulics, and hydrology are the foundation for understanding water supply and pollution control. Chemical principles find their greatest application in water processing, while wastewater treatment relies on biological systems. Knowledge of hydraulics is the key to water distribution and wastewater collection. Quality of the water environment is the

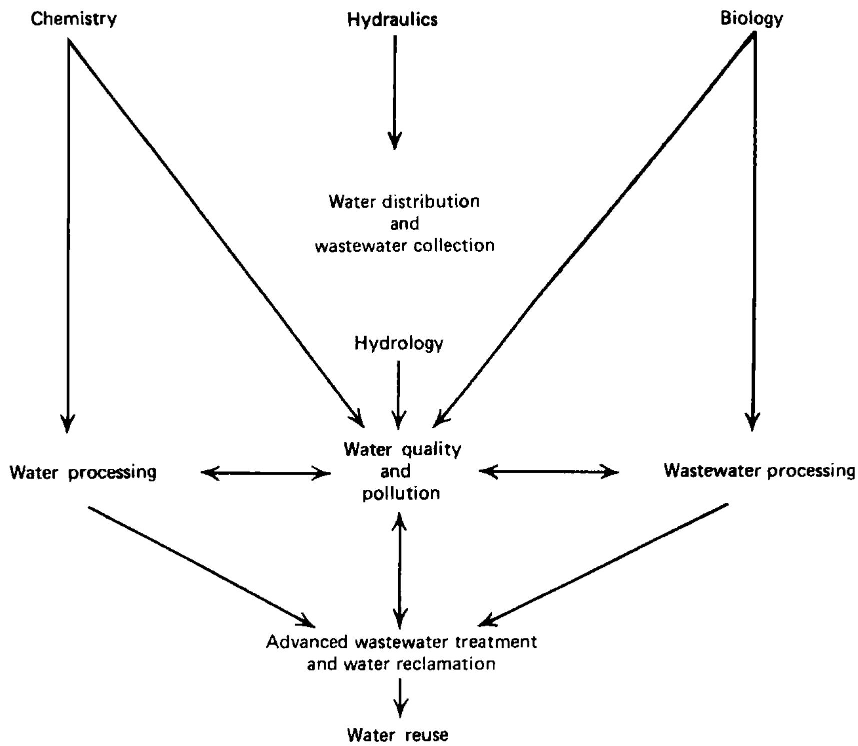

Figure 1–2
Flow diagram relating basic science areas to the disciplines of water and wastewater technology and the integration of various aspects of water supply and pollution control.

focus of the indirect water reuse cycle. As illustrated in Figure 1–2, chemistry, hydrology, biology, water processing, and wastewater treatment converge to give a perception of water quality and pollution. Finally, insights to future direct water reuse are provided through the technology of advanced wastewater treatment and water reclamation.

In this book the fundamental principles of science are integrated with different aspects of sanitary technology. Table 1–1 lists prerequisite readings included in this book for various subject areas. The purpose of this table is to help the student correlate information from the text on a particular subject of interest. For example, prior to studying water quality and pollution in Chapter 5, a student should review chemistry fundamentals, aquatic organisms from bacteria through fishes, the aquatic food chain, waterborne diseases, and the hydrology of rivers and lakes. Prerequisite readings for water distribution systems are selections from Chapter 4. The instructor who is preparing a lecture sequence on this topic may prefer to integrate the principles of hydraulics with the descriptive material from the chapter on water distribution. The advantage is that students can read about real pipe networks while solving simplified pipe flow problems. Conversely, when water processing is taught, it may be most advantageous for the student to review the portions on chemistry listed in Table 1–1 prior to doing the reading assignments in Chapter 7.

Wastewater flows and characteristics are discussed separately in Chapter 9, since this information is needed for both collection systems and wastewater processing. The listing under collection systems also includes applied hydraulics. Conventional municipal wastewater treatment relies on biological processing, and therefore an understanding of living systems is indispensable. The chapters on operation of systems are not intended to give all-inclusive subject coverage. Since this book deals primarily with art and practice, a great deal of information relative to operation is presented throughout the book's descriptive material.

Advanced wastewater treatment incorporates both biological unit operations and chemical processes that are similar to those applied in water treatment. Therefore, to understand the concepts described in Chapter 13, the reader must have adequate knowledge about the handling of both wastewater and water. Reuse of reclaimed water employs the most recent treatment technology and requires a comprehensive understanding of both treatment processes and water quality.

Table 1-1

Listing of Prerequisite Readings for Various Subject Areas in Water and Wastewater Technology

Water Quality and Pollution, Chapter 5	
2–1	Elements, Radicals, and Compounds
2–9	Organic Compounds
2–11	Laboratory Chemical Analyses
3–1	Bacteria and Fungi
3–2	Viruses
3–3	Algae
3–4	Protozoa and Multicellular Animals
3–5	Fishes
3–6	Aquatic Food Chain
3–7	Waterborne Diseases
3–8	Coliform Bacteria as Indicator Organisms
4–12	Flow in Streams and Rivers
4–13	Hydrology of Lakes and Reservoirs
4–14	Groundwater Hydrology
Water Distribution Systems, Chapter 6	
4–1	Water Pressure
4–2	Pressure-Velocity-Head Relationships
4–3	Flow in Pipes under Pressure
4–4	Centrifugal Pump Characteristics
4–5	System Characteristics
4–6	Equivalent Pipes
4–7	Computer Analysis of Pipe Networks
4–9	Flow Measurement in Pipes
Water Processing, Chapter 7	
2–1	Elements, Radicals, and Compounds
2–2	Chemical Water Analysis
2–3	Hydrogen Ion Concentration and pH
2–4	Chemical Equilibria
2–5	Chemical Kinetics
2–6	Gas Solubility
2–7	Alkalinity
2–8	Colloids and Coagulation
2–11	Laboratory Chemical Analyses
4–1	Water Pressure
4–2	Pressure-Velocity-Head Relationships
4–9	Flow Measurement in Pipes
Wastewater Collection Systems, Chapter 10	
4–1	Water Pressure
4–2	Pressure-Velocity-Head Relationships
4–4	Centrifugal Pump Characteristics
4–5	System Characteristics
4–8	Gravity Flow in Circular Pipes
4–10	Flow Measurement in Open Channels
4–11	Amount of Storm Runoff
Chapter 9	Wastewater Flows and Characteristics
Wastewater Processing, Chapter 11	
2–9	Organic Compounds
2–10	Organic Matter in Wastewater
3–1	Bacteria and Fungi
3–3	Algae
3–4	Protozoa and Multicellular Animals
3–11	Biochemical Oxygen Demand
3–12	Biological Treatment Systems
3–13	Biological Kinetics
4–1	Water Pressure
4–2	Pressure-Velocity-Head Relationships
4–10	Flow Measurement in Open Channels
Chapter 9	Wastewater Flows and Characteristics
Operation of Waterworks, Chapter 8	
Chapter 5	Water Quality and Pollution
Chapter 6	Water Distribution Systems
Chapter 7	Water Processing
Operation of Wastewater Systems, Chapter 12	
Chapter 5	Water Quality and Pollution
Chapter 9	Wastewater Flows and Characteristics
Chapter 10	Wastewater Collection Systems
Chapter 11	Wastewater Processing
Advanced Wastewater Treatment, Chapter 13	
Wastewater Processing Plus Prerequisites	
Water Processing Plus Prerequisites	
Water Reuse and Land Disposal, Chapter 14	
Water Quality and Pollution Plus Prerequisites	
Wastewater Processing Plus Prerequisites	
Water Processing Plus Prerequisites	
Advanced Wastewater Treatment	

Chapter 2

Chemistry

This chapter provides basic information about chemistry as it applies to water and wastewater technology. Selected data are compiled and presented as an introduction to the chapters dealing with water quality, pollution, and chemical-treatment processes. For example, the characteristics of common elements, radicals, and inorganic compounds are tabulated. The usual method for presenting chemical water analysis is described, since it is not normally presented in general chemistry textbooks. Sections on chemical reactions, alkalinity, and coagulation emphasize important aspects of applied water chemistry. Since organic chemistry traditionally has not been included in introductory courses, persons practicing in water supply and pollution control are not generally exposed to this area of chemistry. For this reason an introduction on the nomenclature of organic compounds and a brief description of the organic matter in wastewater are provided. Finally, the importance, technique, and equipment used in selected laboratory analyses are discussed. Water-quality parameters and their characteristics can be understood better when testing procedures are known.

2–1 ELEMENTS, RADICALS, AND COMPOUNDS

The fundamental chemical identities that form all substances are referred to as elements. Each element differs from any other in weight, size, and chemical properties. Names of elements common to water and wastewater technology along with their symbols, atomic weights, common valence, and equivalent weights are given in Table 2–1. Symbols for elements are used in writing chemical formulas and equations.

Atomic weight is the weight of an element relative to that of hydrogen, which has an atomic weight of unity. This weight expressed in grams is called one gram atomic weight of the element. For example, one gram atomic weight of aluminum (Al) is 27.0 grams. Equivalent or combining weight of an element is equal to atomic weight divided by the valence.

Table 2–1

Basic Information on Common Elements

Name	Symbol	Atomic Weight	Common Valence	Equivalent Weight[a]
Aluminum	Al	27.0	3+	9.0
Arsenic	As	74.9	3+	25.0
Barium	Ba	137.3	2+	68.7
Boron	B	10.8	3+	3.6
Bromine	Br	79.9	1−	79.9
Cadmium	Cd	112.4	2+	56.2
Calcium	Ca	40.1	2+	20.0
Carbon	C	12.0	4−	
Chlorine	Cl	35.5	1−	35.5
Chromium	Cr	52.0	3+	17.3
			6+	
Copper	Cu	63.5	2+	31.8
Fluorine	F	19.0	1−	19.0
Hydrogen	H	1.0	1+	1.0
Iodine	I	126.9	1−	126.9
Iron	Fe	55.8	2+	27.9
			3+	
Lead	Pb	207.2	2+	103.6
Magnesium	Mg	24.3	2+	12.2
Manganese	Mn	54.9	2+	27.5
			4+	
			7+	
Mercury	Hg	200.6	2+	100.3
Nickel	Ni	58.7	2+	29.4
Nitrogen	N	14.0	3−	
			5+	
Oxygen	O	16.0	2−	8.0
Phosphorus	P	31.0	5+	6.0
Potassium	K	39.1	1+	39.1
Selenium	Se	79.0	6+	13.1
Silicon	Si	28.1	4+	6.5
Silver	Ag	107.9	1+	107.9
Sodium	Na	23.0	1+	23.0
Sulfur	S	32.1	2−	16.0
Zinc	Zn	65.4	2+	32.7

[a]Equivalent weight (combining weight) equals atomic weight divided by valence.

Some elements appear in nature as gases, for example, hydrogen, oxygen, and nitrogen; mercury appears as a liquid; others appear as pure solids, for instance, carbon, sulfur, phosphorus, calcium, copper, and zinc; and many occur in chemical combination with each other in compounds. Atoms of one element unite with those of another in a definite ratio defined by their valence. Valence is the combining power of an element based on that of the hydrogen atom, which has an assigned value of 1. Thus, an element with a valence of 2+ can replace two hydrogen atoms in a compound, or in the case of 2− can react with two hydrogen atoms. Sodium has a valence of 1+, while chlorine has a valence of 1−; therefore, one sodium atom combines with one chlorine atom to form sodium chloride (NaCl), common salt. Nitrogen at a valence of 3− can combine with three hydrogen atoms to form ammonia gas (NH_3). The weight of a compound, equal to the sum of the weights of the combined elements, is referred to as molecular weight, or simply mole. The molecular weight of NaCl is 58.4 grams, while one mole of ammonia gas is 17.0 grams.

Certain groupings of atoms act together as a unit in a large number of different molecules. These, referred to as radicals, are given special names, such as the hydroxyl group (OH^-). The most common radicals in ionized form are listed in Table 2–2. Radicals themselves are not compounds but join with other elements to form compounds. Data on inorganic compounds common to water and wastewater chemistry are given in Table 2–3. The proper name, formula, and molecular weight are included for all of the chemicals listed. Popular names, for example, alum for aluminum sulfate, are included in brackets. For chemicals used in water treatment, one common use is given; many have other applications not included. Equivalent weights for compounds and hypothetical combinations, for example, $Ca(HCO_3)_2$, involved in treatment are provided.

EXAMPLE 2–1

Calculate the molecular and equivalent weights of ferric sulfate.

Table 2–2

Common Radicals Encountered in Water

Name	Formula	Molecular Weight	Electrical Charge	Equivalent Weight
Ammonium	NH_4^+	18.0	1+	18.0
Hydroxyl	OH^-	17.0	1−	17.0
Bicarbonate	HCO_3^-	61.0	1−	61.0
Carbonate	$CO_3^=$	60.0	2−	30.0
Orthophosphate	$PO_4^{\equiv}$	95.0	3−	31.7
Orthophosphate, monohydrogen	$HPO_4^=$	96.0	2−	48.0
Orthophosphate, dihydrogen	$H_2PO_4^-$	97.0	1−	97.0
Bisulfate	HSO_4^-	97.0	1−	97.0
Sulfate	$SO_4^=$	96.0	2−	48.0
Bisulfite	HSO_3^-	81.0	1−	81.0
Sulfite	$SO_3^=$	80.0	2−	40.0
Nitrite	NO_2^-	46.0	1−	46.0
Nitrate	NO_3^-	62.0	1−	62.0
Hypochlorite	OCl^-	51.5	1−	51.5

Solution

The formula from Table 2–3 is $Fe_2(SO_4)_3$.

Using atomic weight data from Table 2–1,

$$\begin{array}{ll} Fe & 2 \times 55.8 = 111.6 \\ S & 3 \times 32.1 = 96.3 \\ O & 12 \times 16.0 = \underline{192.0} \end{array}$$

Molecular weight = 399.9 or 400 grams

The ferric (oxide iron) atom has a valence of 3+, thus a compound with 2 ferric atoms has a total electrical charge of 6+. (Three sulfate radicals have a total of 6− charges).

$$\text{Equivalent weight} = \frac{\text{molecular weight}}{\text{electrical charge}} = \frac{400}{6} = 66.7 \text{ grams per equivalent weight}$$

■■■

2–2 CHEMICAL WATER ANALYSIS

When placed in water, inorganic compounds dissociate into electrically charged atoms and radicals referred to as ions. This breakdown of substances into their constituent ions is called ionization. An ion is represented by the chemical symbol of the element, or radical, followed by superscript $^+$ or $^-$ signs to indicate the number of unit charges on the ion. Consider the following: sodium, Na^+, chloride, Cl^-, aluminum, Al^{+++}, ammonium, NH_4^+, and sulfate, $SO_4^=$.

Laboratory tests on water, such as those outlined in Section 2–11, determine concentrations of particular ions in solution. Test results are normally expressed as weight of the element or radical in milligrams per liter of water, abbreviated as mg/l. Some books use the term parts per million (ppm), which is for practical purposes identical in meaning to mg/l, since 1 liter of water weighs 1,000,000 milligrams. In other words, 1 mg per liter (mg/l) equals 1 mg in 1,000,000 mg, which is the same as 1 part by weight in 1 million parts by weight

Table 2–3

Basic Information on Common Inorganic Chemicals

Name	Formula	Common Usage	Molecular Weight	Equivalent Weight
Activated carbon	C	Taste and odor control	12.0	n.a.[a]
Aluminum sulfate (filter alum)	$Al_2(SO_4)_3 \cdot 14.3H_2O$	Coagulation	600	100
Aluminum hydroxide	$Al(OH)_3$	(Hypothetical combination)	78.0	26.0
Ammonia	NH_3	Chloramine disinfection	17.0	n.a.
Ammonium fluosilicate	$(NH_4)_2SiF_6$	Fluoridation	178	n.a.
Ammonium sulfate	$(NH_4)_2SO_4$	Coagulation	132	66.1
Calcium bicarbonate	$Ca(HCO_3)_2$	(Hypothetical combination)	162	81.0
Calcium carbonate	$CaCO_3$	Corrosion control	100	50.0
Calcium fluoride	CaF_2	Fluoridation	78.1	n.a.
Calcium hydroxide	$Ca(OH)_2$	Softening	74.1	37.0
Calcium hypochlorite	$Ca(OCl)_2 \cdot 2H_2O$	Disinfection	179	n.a.
Calcium oxide (lime)	CaO	Softening	56.1	28.0
Carbon dioxide	CO_2	Recarbonation	44.0	22.0
Chlorine	Cl_2	Disinfection	71.0	n.a.
Chlorine dioxide	ClO_2	Taste and odor control	67.0	n.a.
Copper sulfate	$CuSO_4$	Algae control	160	79.8
Ferric chloride	$FeCl_3$	Coagulation	162	54.1
Ferric hydroxide	$Fe(OH)_3$	(Hypothetical combination)	107	35.6
Ferric sulfate	$Fe_2(SO_4)_3$	Coagulation	400	66.7
Ferrous sulfate (copperas)	$FeSO_4 \cdot 7H_2O$	Coagulation	278	139
Fluosilicic acid	H_2SiF_6	Fluoridation	144	n.a.
Hydrochloric acid	HCl	n.a.	36.5	36.5
Magnesium hydroxide	$Mg(OH)_2$	Defluoridation	58.3	29.2
Oxygen	O_2	Aeration	32.0	16.0
Ozone	O_3	Disinfection	48.0	n.a.
Potassium permanganate	$KMnO_4$	Oxidation	158	n.a.
Sodium aluminate	$NaAlO_2$	Coagulation	82.0	n.a.
Sodium bicarbonate (baking soda)	$NaHCO_3$	pH adjustment	84.0	84.0
Sodium carbonate (soda ash)	Na_2CO_3	Softening	106	53.0
Sodium chloride (common salt)	$NaCl$	Ion-exchanger regeneration	58.4	58.4
Sodium fluoride	NaF	Fluoridation	42.0	n.a.
Sodium hexametaphosphate	$(NaPO_3)_n$	Corrosion control	n.a.	n.a.
Sodium hydroxide	$NaOH$	pH adjustment	40.0	40.0
Sodium hypochlorite	$NaOCl$	Disinfection	74.4	n.a.
Sodium silicate	Na_4SiO_4	Coagulation aid	184	n.a.
Sodium fluosilicate	Na_2SiF_6	Fluoridation	188	n.a.
Sodium thiosulfate	$Na_2S_2O_3$	Dechlorination	158	n.a.
Sulphur dioxide	SO_2	Dechlorination	64.1	n.a.
Sulfuric acid	H_2SO_4	pH adjustment	98.1	49.0
Water	H_2O	n.a.	18.01	n.a.

[a]n.a. = not applicable.

(1 ppm). The concentration of a substance in solution can also be expressed in milliequivalents per liter (meq/l), representing the combining weight of the ion, radical, or compound. Milliequivalents can be calculated from milligrams per liter by

$$\text{meq/l} = \text{mg/l} \times \frac{\text{valence}}{\text{atomic weight}} = \frac{\text{mg/l}}{\text{equivalent weight}} \qquad (2\text{–}1)$$

In the case of a radical or compound the equation reads

$$\text{meq/l} = \text{mg/l} \times \frac{\text{electrical charge}}{\text{molecular weight}} = \frac{\text{mg/l}}{\text{equivalent weight}} \qquad (2\text{–}2)$$

Equivalent weights for selected elements, radicals, and inorganic compounds are given in Tables 2–1, 2–2, and 2–3, respectively.

A typical chemical water analysis is in Table 2–4. These data can be compared against the chemical characteristics specified by the drinking water standards to determine the treatment required before domestic or industrial use.

Reporting results in milligrams per liter in tabular form is not convenient for visualizing the chemical composition of a water. Therefore, results are often expressed in milliequivalents per liter, which permits graphical presentation and a quick check on the accuracy of the analyses for major ions. The sum of the milliequivalents per liter of the cations (positive radicals) must equal the sum of the anions (negative radicals). In a perfect evaluation they would be exactly the same, since a water in equilibrium is electrically balanced. Graphical presentation of a water analysis using milliequivalents is performed by plotting the milliequivalents per liter values to scale, for example, by letting 1 meq/l equal 1 inch. The bar graph shown in Figure 2–1 is based on the water data in Table 2–4. The top row consists of the major cations arranged in the order calcium, magnesium, sodium, and potassium. The under row is arranged in the sequence of bicarbonate, sulfate, and chloride.

Hypothetical combinations of the positive and negative ions can be developed from a bar graph as in Figure 2–1. These combinations are particularly helpful in considering lime water softening. In Figure 2–1, the carbonate hardness [$Ca(HCO_3)_2$ + $Mg(HCO_3)_2$] is 2.15 meq/l and the noncarbonate is 0.45 meq/l ($MgSO_4$).

Table 2–4

Chemical Analysis of a Surface Water (Values in mg/l)

Alkalinity (as $CaCO_3$)	108	Magnesium	9.9
Arsenic	0	Nitrate	2.2
Barium	0	pH (in pH units)	7.6
Bicarbonate	131	Phosphorus (total inorganic)	0.5
Cadmium	0	Potassium	3.9
Calcium	35.8	Selenium	0
Chloride	7.1	Silver	0
Chromium	0	Sodium	4.6
Copper	0.10	Sulfate	26.4
Fluoride	0.2	Total dissolved solids	220
Iron plus manganese	0.13	Turbidity (in NTU[a])	5
Iron	0.10	Trihalomethanes	0
Lead	0	Units of color (in color units)	5

[a]Nephelometric turbidity units