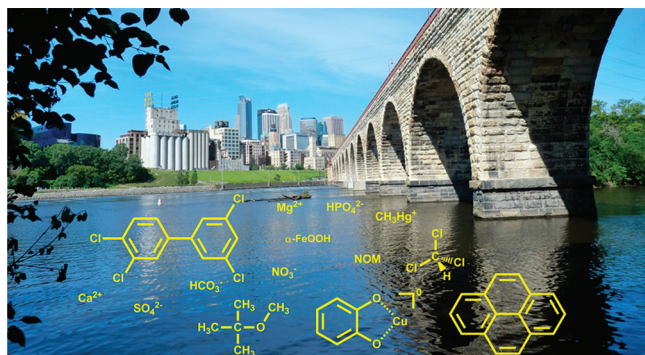


Water Chemistry: Fifty Years of Change and Progress

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■ INTRODUCTION

Most fields of science evolve rather than being invented as a result of someone's sudden burst of inspiration. Water chemistry—the science focused on understanding the chemical processes that affect the composition of natural waters and their suitability for human uses—is a field that evolved from early foundations in several related disciplines. As such, it is difficult to associate a precise date to its founding. Nonetheless, several key events support the argument that water chemistry as we know it today developed in the middle of the 20th century (late 1950s to early 1960s)—at the dawn of the “environmental era.” If we take the midpoint of this period as 1960 or so, this means that the field in its modern incarnation is about 50 years old. In celebration of this half-centenary, we examine here the origins of water chemistry and describe how the field has changed since its formation, focusing on both the “practice” of water chemistry and the ways that teaching the subject have evolved.

■ ORIGINS OF WATER CHEMISTRY

The origins of water chemistry as a subarea of specialization in other disciplines date back more than a hundred years. For example, the chemical composition of lakes and other fresh waters has been of interest in limnology since its development in the late 19th century. The pioneering efforts of Birge, Juday, and co-workers at the University of Wisconsin to understand how lakes behave included extensive chemical studies (e.g., on dissolved gases, nutrients, major/minor ions, and natural organic matter) in the lake district of northern Wisconsin.^{1–3} Hutchinson's classic *Treatise on Limnology*⁴ provides a thorough review of chemical studies on the world's lakes through the first half of the 20th century. Chemical studies on the oceans go back much further, starting with Robert Boyle, considered the founder of chemical oceanography,⁵ who in 1670 conducted experiments with silver nitrate to determine the “saltiness of seawater.” The major ion composition of seawater became known in the mid-19th century from work of Forchhammer and others, and Dittmar's analyses of 77 samples from the

Challenger expedition in 1884 compare favorably with modern values. Riley's 1965 review of chemical oceanography⁵ shows that this field was well developed by the mid-20th century and had moved beyond the descriptive phase into more fundamental studies on chemical processes in seawater.

Geochemists also have been interested in the chemistry of fresh waters for over a century. For example, a 1911 U.S. Geological Survey report described the inorganic chemical (mineral) composition of numerous groundwater wells and rivers in Kansas.⁶ The introduction of this report provides a surprisingly thorough description of the geochemical sources of the ions and their chemical and water quality significance. An even earlier USGS report⁷ described the effects of sewage on water quality and included chemical analyses from as early as 1888 for hardness, nitrogen forms, chloride, and oxygen demand in some rivers around New York City.

Water chemistry was an important component of the field of sanitary engineering, as environmental engineering was known prior to the 1960s, in part because of the important role of chemical processes in drinking water treatment. The chlorination of drinking water is credited with dramatic public health benefits. The first full-scale chlorination of drinking water by a utility in the U.S. occurred in 1908 in Jersey City, NJ, and the design was a collaboration between a chemist (John Leal) and an engineer (George Warren Fuller).⁸ Early studies on coagulation by Bartow and Black,^{9,10} who were professors in chemistry departments, and related studies at the start of the modern era¹¹ also had a strong chemical basis.

In many of the above examples, however, water chemistry played a supporting role for the primary scientific field. Analytical and descriptive aspects of water chemistry typically were the focus, and chemistry was viewed mainly as a *tool* to be used by other scientists and engineers rather than a subject worthy of intellectual inquiry in its own right.

Several key events can be cited in the transformation of water chemistry into a broad field with its own intellectual merit (Table 1). Before discussing these events, a more detailed definition of the field of water chemistry is needed. Defining scientific fields is difficult because of the overlapping nature of related scientific disciplines, as illustrated in Figure 1. For purposes of this review, water chemistry focuses on the solutes (and suspended substances) in water occurring in natural environments and systems engineered by humans, as well as the reactions and phase transfer processes that change the concentrations of solutes in water. The theoretical rigor of fundamental chemistry provides the framework for integrating relevant processes across a diverse set of natural and engineered environments. The focus is not so much on water itself but on

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Table 1. Some Key Developments in the Formation of Modern Water Chemistry

1956	Werner Stumm joins Harvard faculty, beginning a career in research and producing PhDs and mentoring postdocs who become leaders in water chemistry and environmental engineering.
1960	Sillen writes seminal paper, <i>The Physical Chemistry of Seawater</i> , ¹² describing its origin as a “geotitration” of basic rocks by volatile acids and describing the chemical speciation of metal ions in seawater, sparking interest in chemical speciation and chemical models of natural waters.
1960	Stumm and Lee ⁶¹ publish paper on kinetics of oxidation of ferrous ion by O ₂ , perhaps the first modern treatment of chemical kinetics applied to natural water conditions.
1962	G. Fred Lee starts water chemistry graduate program at UW Madison. It emphasized the commonality of chemical principles across all kinds of natural and engineered waters, forged links with scientists in related fields, and developed a multidisciplinary perspective that continues today.
1966	Important ACS symposium held in Pittsburgh on equilibrium concepts in natural waters. ²⁵
1967	Under initial editorship of J. J. Morgan, <i>Environmental Science & Technology</i> begins publication as first major journal outlet focused on water chemistry and more broadly for environmental science and engineering.
1972	Publication by Morel and Morgan of paper ¹⁸ describing REDEQL, the first widely used, broad-based computer program to solve ionic equilibrium problems.

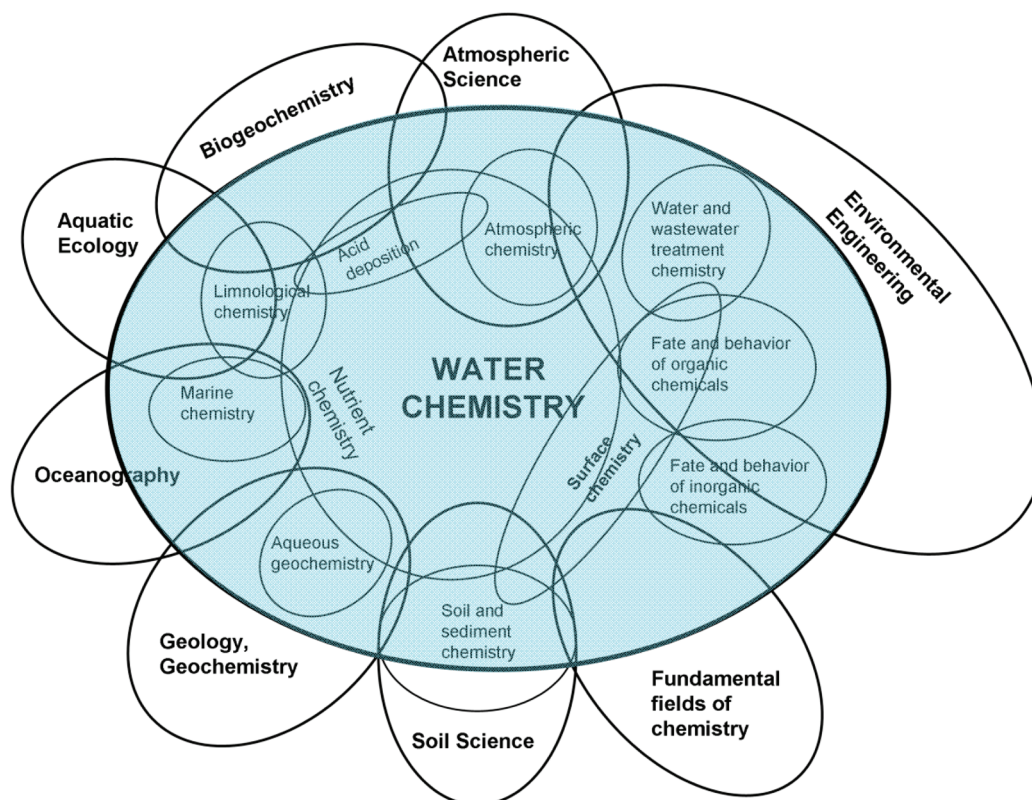


Figure 1. Overlapping neighborhoods of the subfields in water chemistry and related environmental/earth science disciplines. The sizes of ovals are not intended to indicate the importance of any subfield or discipline, and the extent of overlap of the ovals reflects drawing limitations more than extent of concordance among the subfields and disciplines. Modified slightly from ref 35 and used with permission of Oxford University Press.

what is *in* water; nonetheless, the unique characteristics of water as a solvent determine the rates and types of reactions/phase transfer processes that occur. Furthermore, water chemistry generally focuses on temperatures between 0 and 40 °C, on pH values between ~5 and ~9 (with exceptions related to volcanic activity, acidic rainfall, and hazardous wastes), and on both dilute concentrations and saline systems.

Among the key events transforming water chemistry into its present form is the seminal 1961 article, *The Physical Chemistry of Seawater*,¹² written by Lars Sillen (1916–1970), a Swedish inorganic chemist. The article examined the geochemical origins of seawater and insightfully described its chemistry as resulting from a “geotitration” of basic rocks by volatile acids, such as carbon dioxide and acids from volcanic emissions. This descriptive model stimulated many other studies and articles on the geochemical origins of natural waters, which led to the long-

standing interests of water chemists and geochemists in chemical models¹³ and weathering processes. Sillen’s paper also described the “speciation” of numerous metal ions in seawater—that is, the chemical complexes in which they occur in seawater. This analysis spurred much further research (e.g.,^{14–16}) on quantifying the chemical composition of natural waters, and these efforts stimulated the development of computer codes to calculate chemical speciation in aquatic systems.^{17–22}

Simultaneously, environmental engineering was evolving from its narrower predecessor, sanitary engineering, which had been focused on drinking water and wastewater treatment, to encompass the broader goals of understanding environmental systems, including atmospheric and terrestrial components, and developing the technical tools to protect, manage, and restore environmental quality. Leaders of this emerging field realized that a more fundamental approach was needed to

provide scientific underpinnings to environmental policy and management. To the extent that modern water chemistry was developed by scientists and engineers working in or associated with environmental engineering programs, an engineering perspective played an important role in developing the field of water chemistry, but the continued role of chemical oceanographers, limnologists, and geochemists was also crucial.

Academic programs initiated around 1960 that were associated with engineering programs, such as those by Werner Stumm at Harvard University and G. Fred Lee at the University of Wisconsin, espoused an approach to water chemistry emphasizing fundamental scientific rigor and quantitative approaches involving the cornerstones of physical chemistry—thermodynamics and kinetics. These programs also emphasized the commonality of chemical principles across all kinds of natural and engineered water systems and forged links with marine chemists, limnologists, soil chemists, and scientists in other related fields. Water chemistry was, and is, linked to a wide range of earth and environmental sciences (Figure 1). A multidisciplinary perspective that includes, but is not limited to, the principles of chemistry long has been considered essential for a holistic understanding of the *biogeochemical* processes that affect the status of aquatic environments.

Another landmark in the development of water chemistry was the 1967 founding of *Environmental Science & Technology*, a result of efforts by some of the field's early leaders to convince the American Chemical Society to have a journal devoted to environmental chemistry. *ES&T* soon became a major outlet for publishing research in water chemistry and more broadly across the fields of environmental science and engineering. With strong leadership from its editors over the past 45 years, the journal has continued to grow in readership, number of articles published annually, and stature within the scientific community. Several other chemistry-oriented journals, such as *Water Research* (also founded in 1967), *Chemosphere* (1972), and *Environmental Toxicology & Chemistry* (1982), as well as those established in more recent decades, demonstrate the vitality of the field.

■ WHAT IS ITS NAME?

The origins of the term *water chemistry* are obscure, but given its simplicity and appropriateness for the chemical science that focuses on water, it is no surprise that the term has been used for many decades. An American Chemical Society division called *Water, Sewage, and Sanitation Chemistry* regularly held sessions at national meetings (except in 1945) starting in 1925. The division's name was changed to *Water, Air, and Waste Chemistry* in 1958 and to *Environmental Chemistry* in 1973. John Baylis, a pioneer in water treatment chemistry, used the term "water chemist" in a 1927 article:²³ "More and more it becomes evident that the problem is one for the water chemist to solve by treating the water to prevent deterioration of the pipes rather than to continue searching for non-corrosive materials." The focus of "water chemists" prior to the early 1960s seems, however, to have been on water *treatment* chemistry and not the broad array of topics characterizing the field today.

The first use of the term "water chemistry" for an academic program was for a program at the University of Wisconsin in Madison founded by G. Fred Lee in 1962 as an expansion of an earlier program called Sanitary Chemistry. The first use of the

term for a conference apparently was for the 1965 Rudolfs Conference, *Principles and Applications of Water Chemistry*, at Rutgers University. The editors of the conference proceedings²⁴ commented in their preface "...a new expression, a new term, is spreading throughout the profession 'water chemistry.' This 'new' chemistry is receiving considerable attention in didactic and research circles." The above discussion thus suggests that use of the term water chemistry became commonplace in the early to mid-1960s.

The generally synonymous term *aquatic chemistry* apparently was coined by Werner Stumm in the preface to the book *Equilibrium Concepts in Natural Waters*,²⁵ based on a 1966 ACS symposium. According to his long-time colleague, James J. Morgan (Pers. comm., 2011), Stumm wanted to achieve a blending of two strands of water research: (i) the European and U.S. schools of water treatment chemistry and (ii) the "hydrochemistry" schools in Scandinavia and the USGS. He chose "aquatic", which tilted somewhat to the natural systems side. The titles of textbooks published in the field over the past 40 years are split approximately evenly between the terms, water chemistry and aquatic chemistry. It is interesting to note that the only U.S. graduate degree program devoted exclusively to this subject (at the University of Wisconsin in Madison) changed its name from "Water Chemistry" to "Environmental Chemistry and Technology" in 2001 and "Aquatic Chemistry" now is one of its areas of specialization.

■ WATER CHEMISTRY COURSES AND TEXTBOOKS

The teaching of modern water chemistry in its first decade was considerably different from current teaching practices. New courses were developed based on physical-chemical principles to supplement (or in some cases supplant) earlier courses based on analytical chemistry (water and wastewater analysis). No textbooks existed for the new courses, and instructors often relied on "handouts" obtained from courses they had taken from founding fathers of the field. Textbooks that covered only parts of the subject and/or were aimed at other fields^{26–28} also were used. The subject matter focused on inorganic equilibrium chemistry and much attention was devoted to solving ionic equilibrium problems. Because computer programs were not yet available, problems were solved by tedious manual solution of the defining algebraic equations, which usually required making many simplifying assumptions. Graphical methods to display and solve acid–base, solubility and redox equilibrium problems (such as pC–pH and Pourbaix diagrams) also were emphasized. Little attention was paid to teaching the fundamentals of thermodynamics and kinetics; instructors generally assumed that students had gained such knowledge from physical chemistry or related courses. Kinetics received less attention than chemical equilibria, and almost no attention was paid to organic constituents in water, especially synthetic organic compounds present as a result of human activity, or to surface chemistry processes.

No major field of science can exist for long without an organizing framework articulated in a textbook. Building upon important foundations provided by two earlier texts on aqueous geochemistry by Garrels and Christ²⁶ and Butler,²⁷ Stumm and Morgan provided this perspective in 1970 in the discipline's first authoritative text, *Aquatic Chemistry*.²⁹ Through three editions, the most recent published in 1996, *Aquatic Chemistry* became increasingly more comprehensive and continued to set the standard for the field. In its quantitative orientation and

focus on both understanding systems *and* solving problems, the text has an environmental engineering orientation, but it provides a highly multidisciplinary approach to understanding the chemistry of water in both natural and engineered environments.

Several other textbooks^{30–35} similar in approach but not necessarily in scope to Stumm and Morgan's books have been published over the past 30 years. These books generally were written to provide a more didactic approach for students with limited academic backgrounds in chemistry, and most^{30–34} focus primarily (or exclusively) on inorganic equilibrium chemistry. Although this may be understandable in terms of the historical orientation of the field, it does not reflect its current scope. Except for more recent texts^{33–35} these books largely emphasized manual approaches (algebraic and graphical) to solving chemical equilibrium problems. Several computer programs^{21,22} now are available to solve such problems. In addition, several books oriented specifically toward aqueous geochemistry courses in Geoscience departments also have been published,^{36,37} and a few water/environmental chemistry texts have taken different approaches to the subject.^{38–40}

Despite the importance of organic contaminants in water quality and aquatic ecosystem health and the massive amount of research undertaken for more than 40 years to understand the sources, behavior, fate, and effects of these compounds, most introductory water chemistry textbooks do not cover this important subject. Exceptions include Sawyer et al.³⁸ and the recent textbook we published.³⁵ The subject is covered extensively by Schwarzenbach et al.⁴¹ in their seminal book on the environmental aquatic chemistry of organic contaminants and in several texts with more focused scopes.^{42–44} These books are used as texts by many environmental engineering programs for separate courses focused on the fate of organic pollutants. For students whose exposure to water chemistry is limited to a single class, an introduction to the chemistry of organic pollutants in aquatic systems is certainly warranted.

■ HOW HAS WATER CHEMISTRY CHANGED OVER THE PAST 50 YEARS?

Driven by three primary forces, the field of water chemistry has changed dramatically since its synthesis from the predecessor fields described previously. The primary drivers for change were: (1) environmental quality and pollution issues that had a chemical focus; (2) advances in scientific approaches and technology; and (3) advances within the field that led to new areas or ways to study existing areas. We present examples of each driving force in turn.

Pollution as a Driver for Water Chemistry Advances.

Given the importance of clean water for human use and environmental quality, it is not surprising that major chemical pollution issues have been important drivers for research in water chemistry. The first large issue driving modern water chemistry research was nutrient overenrichment of lakes (eutrophication) in the 1960s–1970s. Much was learned, mostly through government-funded research, about nutrient cycling processes in aquatic systems (e.g., chemical nature and behavior of phosphorus and nitrogen in water, sediment–water exchange processes, chemical removal of phosphorus from wastewater, and ways to manage the consequences of nutrient enrichment and rehabilitate damaged lakes). Nonetheless, for reasons related more to economics and social behavior than to scientific limitations, the problem was not really resolved. Nutrient pollution remains a major cause of degraded water quality today. In the 1990s, the problem “morphed” into the issue of

hypoxia in coastal waters—depletion of oxygen in bottom waters by high loadings of planktonic organic matter, formation of which is stimulated by excessive nutrients. Research spawned by this issue has focused on nutrient dynamics at landscape-level understanding.

Acid rain (or acid deposition) was a major driver for research from the mid-1970s to early 1990s. In addition to advancing our knowledge on rainfall chemistry and dry deposition processes, research addressing this problem improved our understanding of the kinetics and mechanisms of mineral weathering in soils and watersheds, as well the chemistry of soft-water lakes and streams, including in situ alkalinity-generation (or acid consumption) processes. A similar issue—mercury pollution—became a concern in the late 1980s and stimulated research on related biogeochemical processes that continues today. Earlier concerns about Hg in the 1960s arose primarily from its use in industry (e.g., as electrodes in chlor-alkali plants). When these sources were controlled, scientists discovered that atmospheric transport of Hg primarily from coal combustion was causing widespread contamination, leading to fish consumption advisories for lakes and concern about toxic impacts of Hg on wildlife.

The finding of toxic chlorinated organic compounds like chloroform and other trihalomethanes, more generally known as disinfection byproducts (DBPs), in drinking water in the early 1970s stimulated much research on chlorine chemistry and DBP formation mechanisms that continues to the present. This issue, along with the finding that chlorine was not effective in controlling cysts of pathogenic protozoa (e.g., *Cryptosporidium*), also stimulated research on alternative disinfectants, such as ozone and UV irradiation, and on advanced oxidation processes to remove organic pollutants from water supplies. Finally, research in environmental organic chemistry has shifted focus many times over the past half century, as public concern developed over different classes of organic pollutants. Various pesticides were the focus of studies in the 1960s and 1970s. Major issues with PCBs and PAHs in the 1970s and 1980s led to investigations of atmosphere/water/biota partitioning and connections with toxicologists. Chlorinated solvents, petroleum hydrocarbons, and explosives (as well as heavy metals) received extensive attention after the passage of the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) and the resulting need to remediate ground waters. Endocrine disrupters, pharmaceuticals, and personal care products (so-called emerging contaminants) have been the focus of research in recent years.

Technological Advances. An array of technological advances over the past 50 years has fueled major changes in the topics water chemists study and the ways and ease with which they make measurements. Starting with routine water analysis, in the 1960s most major and minor ions were analyzed by wet chemical procedures, including titrations and colorimetry. Except for alkalinity (still done by titration), routine water analyses today are done mostly by automated or semiautomated instrumental techniques, such as ion chromatography (anions, including some nutrients), atomic absorption spectroscopy, and inductively coupled plasma emission spectroscopy (major, minor, and trace metals). Whereas “trace” concentrations in the 1960s generally were considered to be in the low part-per-billion ($\mu\text{g/L}$) range for metal ions, detection limits now reach parts per trillion values (ng/L) and even lower

Table 2. Recent Advances in Instrumentation Driving Advances in Water Chemistry Research

constituent	instruments/methods	applications
metals	ICP-ES (inductively coupled plasma emission spectrometry)	multiple-element analysis at trace levels (mainly metals)
	ICP-MS (inductively coupled plasma mass spectrometry)	trace-level analysis of metals with ability to measure specific stable isotopes of elements
organic contaminants	GC-IRMS (gas chromatography-isotope ratio mass spectrometry)	allows compound specific isotope analysis to be performed, giving insight into relevant reaction processes/mechanism
	LC-MS/MS (liquid chromatography-triple quadrupole mass spectrometry)	identification and quantification of trace organic pollutants
natural organic matter	FT-ICR-MS (Fourier-transform ion-cyclotron resonance mass spectrometry)	analysis of organic molecules at very high mass resolution (up to 10^{-5} amu) so that unique elemental composition of large molecules can be determined
	Excitation/emission matrix fluorescence spectroscopy	gives information about the composition of organic matter
	EXAFS (extended X-ray absorption fine structure)	determine number, lengths, and orientation of bonds in metal-humic complexes
	XANES (X-ray absorption near edge spectroscopy)	determine oxidation states of elements
surfaces/nanoparticles	Quartz crystal microbalance	interaction of organic matter or nanoparticles with surfaces.
	Scanning probe microscopy	nanometer scale evaluation of mineral dissolution
	Electron microscopy	nanoparticle characterization

for methods like atomic fluorescence spectroscopy (for Hg) and ICP-mass spectrometry (ICP-MS) for many metals. The invention of the electron capture detector allowed the detection of a plethora of halogenated organic pollutants. Mass spectrometry coupled with gas and liquid chromatography has allowed the detection and verification of the identity of trace organic contaminants, and these techniques are now used routinely to measure such compounds accurately and unambiguously. Additional spectroscopic and mass spectrometry techniques (Table 2) have led to advances in characterizing natural organic matter, reaction mechanisms of organic pollutants, and solid-solution interfaces.

Huge advances in computer technology over the past 50 years have revolutionized the conduct of all fields of science, including water chemistry. The ways we store, analyze and graph data, do computations, conduct searches for references and other information, and communicate with colleagues have changed markedly, especially since the advent of personal computers and the Internet. It no longer is necessary to go to a library to do literature searches; instead, access to the world's libraries comes with a few clicks on a computer anywhere that Internet connections are available. As surprising as it may be to many current water chemists, hand-held calculators were unavailable 50 years ago, and "data crunching" was done by hand, slide rule, mechanical calculating machines, or (rarely) by user-unfriendly mainframe computers. More specifically, software programs (Table 3) developed over the past ~40 years allow water chemists to easily solve nonlinear algebraic and differential equations via numerical analysis and produce graphical displays of results in many areas (e.g., metal ion equilibrium speciation, estimating physical-chemical properties of organic compounds, calculating solar irradiance for photochemical rate studies) that typically were impractical in previous years. Advances in molecular/electronic structure modeling have allowed exploration of physical-chemical properties and reaction mechanisms of organic compounds in silico.

Advances Leading to New Topical Areas. Several examples exist where a new idea or finding in a research article

Table 3. Important Software Used in Water Chemistry

name	uses
MINEQL+, Visual MINTEQ, Geochemist's Workbench	acid-base, solubility, complexation, redox equilibrium calculations, and surface complexation modeling
PHREEQC	reaction-transport modeling and chemical speciation
WHAM	equilibrium modeling, especially for ion binding by humic substances
FITEQL	fitting data to functions and to determine equilibrium constants from experimental data
Acuchem, Achem, Tenua, CAIN, Kintecus	chemical kinetics: simulation of complex reaction sequences
GCSOLAR, SMARTS	calculation of light intensity for photochemical reactions
ChemBioDraw	drawing, naming organic structures; molecular dynamics calculations
Gaussian and Jaguar	ab initio molecular dynamics calculations
EPI Suite, SPARC	estimating values of physical-chemical properties of organic compounds

has spawned a new area of research in water chemistry. For example, the finding^{45,46} that molecular oxygen exists in natural waters in a light-activated excited state, singlet oxygen ($^1\text{O}_2$), led to the recognition that sunlight produces several reactive photointermediates in aquatic systems. This finding was seminal to the development in the 1970s of the subfield of aquatic photochemistry, which has shown that photochemical transformations are important in the fate of many organic contaminants in natural waters, as well as in the behavior of NOM and some metals (e.g., Fe, Mn).

Similarly, the recognition that specific adsorption of metal ions to (hydr)oxide surfaces could be viewed as an extension of complexation chemistry led to the concept of "surface complexation."^{29,47,48} This idea greatly expanded the role of chemistry in studying sorption of solutes to charged surfaces, which previously had focused on the physics of the process. Surface complexation models^{17,18,49,50} have improved our quantitative understanding of the role of solution conditions

like pH and ionic strength in the binding of ionic solutes to mineral surfaces.

For organic chemicals, a watershed moment was the public awareness of the links between synthetic organic chemicals and environmental problems initiated by the publication of *Silent Spring*.⁵¹ This led to the need to predict where organic pollutants go and how they react in aquatic systems. Of critical importance was work that combined the equilibrium (i.e., fugacity) concepts of partitioning and the kinetic description of phase transfers and chemical reactions into predictive models.⁵² The result was an emphasis on determining and/or predicting partition coefficients and transformation pathways of organic chemicals based on chemical structure so that their environmental fate could be accurately assessed.

■ CONSTANT THEMES IN THE FIELD

As illustrated above, the field of water chemistry has undergone major changes over the past 50 years. Nonetheless, it has retained four major characteristics from its earliest days. First, its research focuses primarily on issues related to human needs for clean water and environmental quality. Water chemistry thus is highly relevant for societal wellbeing. Second, it encourages a multidisciplinary perspective based on chemical principles but extending across many “neighboring fields” (Figure 1) to improve understanding of the composition and behavior of aquatic environments. Water chemists tend to be comfortable in multidisciplinary teams studying complex environmental problems. Third, water chemists still view their domain to include all environmental waters: fresh and saline, surface and ground waters, in natural and engineered systems, the gaseous and solid phases with which water is in contact, and more recently even blood and other body fluids. Fourth, water chemists always have borrowed concepts and technologies freely from other fields of inquiry, applying them to enhance understanding of chemical processes in aquatic systems. A prime example is the application of structure–activity and property–activity relationships, first developed by pharmacologists, to predict the behavior of organic chemicals in aquatic ecosystems.⁵³ Many other examples could be cited from geology, microbiology, materials science, and many other fields of chemistry. In addition, a few research topics have remained popular from the earliest days of the field to the present, including the chemical behavior of nutrients and trace metals,^{15,16,54} kinetics of iron and manganese redox reactions^{55–59} and the chemical nature and behavior of NOM.^{60–62}

■ SUMMARY AND OPPORTUNITIES

Given the interdisciplinary nature of water chemistry, the field will continue to benefit from advances in materials characterization, molecular biology, and mass spectrometry. Water chemists, who work across scales ranging from molecular to global, are poised to make additional contributions to improve our understanding of important, societally relevant water issues. These include the nature and behavior of NOM and related organic matter in wastewater effluents (EfOM), the role of biomolecules (e.g., genes, prions) as pollutants, critical biogeochemical processes involving carbon, nitrogen and phosphorus in natural systems, and the implications of global climate change on the chemistry of natural waters (including the problem of ocean acidification). Research on the development,

uses, behavior, and fate of nanomaterials, which has grown exponentially over the past decade, will likely continue to be a major research topic for water chemists for many years. Although scientists have had great success finding and responding to new pollutants, additional efforts need to emphasize predicting what chemicals may pose a threat to aquatic environments prior to their release. Improvements in computational techniques will allow such assessments, as well as improved understanding/verification of experimental findings. As growing populations continue to stress water resources, water treatment and reuse will require further technological advances. Water chemistry will continue to play a critical role in the goal to provide sufficient and safe water for the world’s population.

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Notes

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