WHAT WATER QUALITY IS

Matrices of Sources, Uses, Standards, Occurrence and Technology

Water Quality Matrices

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What Water Quality Is

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Introductory

Abel Wolman, Scientist and Engineer of Water Quality

It is an honor for me to share the same lecture with Abel Wolman. I say share, because I feel his presence through the legacy of his wide-ranging writings and wise counsel to the profession and to society. In reading his papers on the quality of water, which span three score years and ten, one feels a keen intelligence, engineering judgment, and dedication to public health. Abel Wolman was among the first sanitary engineers educated in the United States in the twentieth century. After earning both BA (1913) and BS Engineering (1915) degrees from Johns Hopkins, he began early on to initiate research in the Maryland State Department of Health with the aim of making more quantitative the standards of quality for water supplies and chlorinated, filtered drinking waters. One senses at the outset of his professional life a questioning stance toward conventional wisdom on methods and standards, together with a drive to improve engineering practice in the water realm.

His early publications reveal the great importance he attached to accurate measurements and defensible standards for quality of water.
Wolman and Morse\textsuperscript{1} sought a \textit{water quality index} based on three available characteristics in 1918:

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Qindex} & Indicators of Quality & & \\
\hline
 & Watershed protection & & \\
 & Coliform bacteria & & \\
 & Treatment works reliability & & \\
\hline
\end{tabular}
\end{center}

In the last decades of his life Abel Wolman continued to question and reconsider some of the contentious policy issues arising in what he called the new “chemical era” of water quality protection. At length, in a 1986 lecture\textsuperscript{2}, he expressed both his characteristic \textit{pragmatism} and \textit{optimism}: “Not only are the old limits for old parameters being questioned, but criteria are now being sought for entirely new parameters, especially in the field of trace organic materials...We wait upon major scientific clarifications. In the meantime, we should follow our
past fruitful experience by removing them from our potable waters as we continue to do with the more familiar physical [and] biological ones.”

Orbital Overlaps: Bottles, Manganese and James Thurber

Bottles and Rivers: In the summer of 1913 engineering assistant Abel Wolman sampled the waters of the Potomac River with the U.S. Public Health Service. In Abel Wolman’s oral history, according to a very reliable source, Abel Wolman said “his mother never understood why her son – who had just received an advanced degree from the University – seemed to be doing nothing more than collecting bottles of water.” Those water samples he subsequently analyzed for bacterial concentrations. One of the research leaders on the Potomac survey was the biologist and engineer Earle B. Phelps, recalled as “a great” by Abel Wolman in his oral history. That early experience had had “tremendous value” in shaping Abel Wolman’s subsequent life. By a happy sort of coincidence, my own career was also shaped by a first experience in “collecting bottles.” As a new research assistant to Professor Clarence Velz at The University of Michigan I helped sample the Miami River of Ohio in the summer of 1954. My assignment was to collect many samples along a fifty-mile stretch of the river and then analyze them for dissolved oxygen, generating thereby an “oxygen sag” profile of the Miami. Yes, Abel Wolman’s mentor in 1913 was the man later to introduce the “Streeter-Phelps” equation to stream analysis. Still later, Phelps was the graduate adviser to Clarence Velz at Columbia University.
On our respective rivers, four decades apart, Abel Wolman and I were each entering the world of water quality through microbiological and chemical measurements, respectively.

Manganese in Water Supply: Our second water quality overlap concerns the chemistry of manganese in storage reservoirs. I first became interested in the natural water chemistry of manganese in 1960, as a Ph.D. student at Harvard in the water chemistry laboratory of Professor Werner Stumm. For drinking water the standard for manganese was then based on aesthetic concerns about color and precipitation in treated waters. The focus of my study was on experiments designed to define reaction rates of manganese compounds in water. During my work I was pleased to come upon a much earlier paper by Professor Abel Wolman and MS student Robert B. Stegmaier, Jr. of Hopkins. It presented a detailed history of annual cycles of manganese and related chemical substances in the Loch Raven reservoir of the City of Baltimore water supply. Their 1940 paper emphasized that “The occurrence of manganese does not appear to follow the general trends … in surface reservoirs…” The problem of manganese did not commence until the Loch Raven reservoir was filled in 1923. The new seasonal patterns of manganese concentrations were not like those for iron and color in the water. In brief, Wolman and Stegmaier found that manganese had a unique annual reservoir cycle, with peaks in October of each year. Of great interest to my own work was their strong conclusion that the manganese cycle
each year “is closely paralleled by the increase in carbon dioxide and by the reduction in the amount of dissolved oxygen.”

Their hypothesis for seasonal peaks of manganese production in large reservoirs invokes action by microorganisms in deeper waters to oxidize excessive organic compounds released from reservoir sediments. The consequence in deep waters is oxygen depletion and carbon dioxide production. In their scheme, mobilization of manganese from the sediments is a consequence of the lowered pH caused by carbon dioxide generation. (In later years, my student Alan Stone (now a professor at Hopkins) would extend the theory of manganese mobilization from sediments to include electron transfer reactions between manganese dioxide and organic compounds5.) The work of Wolman and Stegmaier is rich in chemical data on manganese occurrence in a major reservoir. Manganese concentration is the quality variable of primary interest. Understanding its behavior in the reservoir calls upon measurements of other concentrations and parameters.

Meaningful water quality measurements need to include not only primary contaminants but major chemical composition data as well.: For example, inorganic carbon, calcium, organic carbon, sulfate, oxygen and other solutes.

James Thurber and Quality: A favorite evening pastime of the Wolman family and their friends the Hollanders was said to be reading aloud from the writings of the humorist James Thurber. I am gratified to learn that the families
were often “convulsed” by these readings. Thurber’s special humor has brought similar pleasures to my own family over the past four decades. And it has often proved instructive. I believe that the following exchange is relevant to a consideration of quality.

A friend once asked James Thurber “How is your wife?” “As compared to what?” he replied.

Qualities of Water

Compared to What?

Metaphor: Water qualities imply comparisons. There are many rich water metaphors: In the Odyssey, some three thousand years ago, Homer sang of the “wine-dark sea.” Kuo Hsi, in the eleventh century, spoke of water as “the blood of the universe.” Francis of Assisi praised God through our “Sister Water, so useful, humble, precious and pure.”

Early Perception: Summarizing characterizations of perceived water qualities have been recorded throughout history. M.N. Baker, in his classic book, The Quest for Pure Water epitomized early human water experience thus: “Water was taken as found. It might be plentiful but muddy, scarce but good, or both scarce and bad … Man’s earliest standards of quality were few: freedoms from mud, taste and color.”

Through many centuries we find a growing number of perceived antipodal water qualities: good or bad, clear or muddy, limpid or cloudy, colored or transparent, sparkling or dull, sweet or bitter, odorless or fetid, clean or foul,
cool or tepid, salubrious or unhealthy, are examples. We might construct an “ur matrix” of water quality for the pre-scientific era. (Many of these water qualities are pertinent to the acceptability of water today. It is a truism that water needs to meet sensory quality standards in order to be welcome.)

<table>
<thead>
<tr>
<th>Q&lt;sub&gt;pre&lt;/sub&gt;</th>
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</thead>
<tbody>
<tr>
<td>Good</td>
</tr>
<tr>
<td>Clear</td>
</tr>
<tr>
<td>Limpid</td>
</tr>
<tr>
<td>Colored</td>
</tr>
<tr>
<td>Sparkling</td>
</tr>
<tr>
<td>Sweet`</td>
</tr>
<tr>
<td>Odorless</td>
</tr>
<tr>
<td>Clean</td>
</tr>
<tr>
<td>Cool `</td>
</tr>
<tr>
<td>Salubrious</td>
</tr>
</tbody>
</table>

**Differing Notions of Water Purity:** Ancient civilizations recognized water purity, but not as we do in the modern era, where *quality* has been made *quantitative*. Through most of recorded history water itself has stood for an unconscious value of purity. Water myths regard water as the elemental stuff of dreams. But, as remarked by Bachelard, “For the modern mind, the difference between pure and impure water is entirely a rational matter.” I would say it is now a matter of *measurement*. The once *either/or* character of quality – comparing pure vs. impure – is now a comparison along a *continuum*: *Pure* - *Impure*
It is essential to identify the *basis* and the *scale* for each water property.

**Basis:** It has been proposed by some students of environmental waters that H₂O is the proper basis in matters of quality. From this viewpoint only water vapor is pure (and that does not consider the isotopes). Raindrops are already “contaminated” by gases and aerosols. Rivers, lakes and ocean are then never “pure.” In my view, most references to “pure water” and “water quality” are not well defined because a *basis* is often absent. The waters of the earth vary widely in their natural chemical *composition*. But, what does it mean to say that they vary in *water quality*? Pure water to ancient societies did not have to do with H₂O, but with those good or bad qualities of waters found around them.

**From Miasma to Water Borne Disease**

*John Snow, Epidemiologist:* Progress in chemistry from the sixteenth century to the nineteenth century notwithstanding, perceptions of relationship between water and disease centered on “corrupting miasmas” arising from accumulations of human waste deposited along rivers by wastewater sewer discharges. The River Thames in the center of London was a case in point. Then, in 1854, Dr. John Snow hypothesized that polluted Thames waters finding their way into the drinking water supply caused epidemic cholera deaths. As related by Dr. Daniel Okun in a recent National Research Council Report, Snow traced high rates of cholera mortality (compared to the rest of London) to piped drinking water drawn from a Thames location downstream from major wastewater discharges.
Snow’s painstaking epidemiologic research revealed that higher cholera death rates were associated with the downstream water intake of the Southwark and Vauxhall water company, whereas lower cholera death rates were associated with the upstream water intake of the Lambeth water company. In brief, the relative cholera death rate associated with the downstream source was 5.7, when compared to the rest of London. The relative death rate associated with the upstream source was 0.7, when compared to the rest of London.

**Risk:** The relative risk of downstream water compared to upstream water on the River Thames in the time of cholera was thus 8.5. We might think of this relative risk as a measure of a water quality difference between the two water sources. Snow’s convincing 1854 demonstration that cholera is a disease carried by contaminated water came almost three decades before Koch’s isolation in 1882 of the bacterium causing cholera and his confirmation of the germ theory of disease.

**Water Quality Lessons:** Lessons could be drawn. First, take drinking supply from the source of highest quality. Second, protect the source from pollution. Third, intervene when necessary, employing engineered water purification processes to improve quality of poorer sources. And how was “quality” measured with respect to water borne disease? Comparison between water of good quality and bad quality in regard to water borne pathogens was initially made, and is still made, using measurements of “indicator microorganisms.” For example, the first United States federal regulation governing water quality was
issued in 1914 for interstate commerce: A maximum total bacteria plate count of 100 per ml of water, and no more than 2 *coli*form* bacteria per 100 ml of water. (It is worth recalling that the paper by Robert Morse and Abel Wolman in 1918⁹ advanced a number of criticisms of these and related measures of “quality of drinking water” as failing to provide a “universal measure of quality,” in part because of imprecise methodology and in part because they thought that biochemical tests and sanitary surveys might also have importance in formulating an “index of water quality.”) In 2003, National Primary Drinking Water Standards in the United States¹⁰ include two “indicators” of bacterial quality: the heterotrophic bacteria plate count and total *coli*form* bacteria (including fecal *coli*form and *E. coli*). There are now several pathogenic microorganisms that are regulated in drinking water: *Cryptosporidium*, *Giardia lamblia*, *Legionella*, and viruses.

**Water quality with respect to microorganisms and water borne disease is now measured by comparison of actual numbers of indicator organisms in drinking water to a permissible level established by law.**

**Water Quality in Our Time**

**Components of Modern Water Quality**

Looking back on pre-scientific times we can see the underlying complexity of inadequately rationalized water qualities as “good” and “bad”. In modern times purity can be rationalized into its underlying components, and these sorted into
biological, chemical, physical, and sensory categories. A water analysis may reveal arsenic, bacteria, disinfection by-products, or other impurities. The result is a quantitative list of individual impurities. By choosing a basis for a property we define a scale of *water quality* for that property. The basis chosen might be either scientific or economic in character:

\[
\begin{array}{c|c}
\text{Basis} & \text{Actual} \\
0 & \\
\hline
\text{Water Quality} & \\
\end{array}
\]

For example, arsenic is a drinking water *contaminant* because it is a carcinogen. *The scientific basis* for judging arsenic as a contaminant is epidemiologic information relating amounts of arsenic consumed in drinking water to reported deaths from lung and bladder cancer. On the basis of the epidemiologic information a *public health goal of zero* for arsenic as a carcinogen has been set by the United States Environmental Protection Agency (EPA).\(^{10}\) The current *standard* is not zero. We will turn to the matter of a standard for arsenic below.

For the moment we return to the earlier example of bacterial contamination in drinking water, recalling that permissible levels are set in terms of indicator organisms rather than individual pathogens. The *public health goal* for total coliforms set by EPA is zero. The *standard* is set as no more than 5% positive tests per month\(^{10}\). Testing for fecal coliforms or E. coli must follow up a
positive coliform result. The objective of this indicator standard is to guard
against drinking water contamination by pathogens.

Some standards for drinking water quality are not expressed directly as
permissible concentrations, but rather as required treatment techniques or
percent removal. The aim for each contaminant is to close the gap between
actual quality and required quality: A maximum arsenic level of 10 microgram per
liter will soon be in force for community drinking waters. For water systems
serving more than 10,000 people, at least 99% removal of cryptosporidium
pathogens by treatment is required. For enteric viruses in a water supply 99.99%
inactivation or removal is required.

**Safe Drinking Water: The Example of Arsenic**

For some time the arsenic drinking water standard was set at 50 micrograms per
liter. The National Research Council concluded in 1999\(^1\) that recent
epidemiologic evidence indicated that human health is not adequately protected
by the current standard. A further critical examination by the National Research
Council was completed in September 2001\(^2\). In January 2006 a new arsenic
standard of 10 microgram per liter will be enforced\(^3\). The U.S. public health goal
for arsenic is zero. Environmental policy calls for setting the standard for
protection as close to the goal as practicable. It is instructive to review briefly the
basis for arriving at the revised national arsenic standard. Scientific information
on human risk and socio-economic considerations both enter into the choice of a
standard for health, safety or well-being. . Risk of bladder and lung cancers
increases with daily arsenic intake. Analysis of epidemiologic results indicates an *increased cancer mortality factor* of approximately $3 \times 10^{-5}$ risk per microgram of arsenic per day. If the standard for arsenic is set at $S$ micrograms per liter, then for a drinking water containing $X$ micrograms arsenic per liter, the *cancer risk reduction* in meeting the standard for the water is proportional to $(X - S) \times$ volume consumed daily. The *cost* of achieving this risk reduction is dependent on $X-S$, in a complex way, for the technologies chosen. There are more than 50,000 community water supplies in the United States. Each supply has an “old” arsenic concentration $X_{\text{old}}$. A recent computation by Gurian, et al.\textsuperscript{14} yielded *total cancer risk reduction* and *total cost* of attaining a “new” concentration standard, $S_{\text{new}}$. The authors summed over all existing U.S. community water supplies and for a range of candidate arsenic standards. Benefits are expressed as national cancer fatalities averted. Total national costs are on the order of several hundred million dollars annually. There are uncertainties in the risk information and also in the estimated total costs of improved arsenic removal. (National treatment cost estimate span a three-fold range at a proposed standard of 10 micrograms per liter.) For a standard of 20 micrograms per liter, a moderate treatment cost scenario yielded an incremental cost per averted fatality of 6 million dollars; for a 10 microgram per liter standard the incremental cost was about 12 million dollars. The U.S. EPA has estimated the benefit of changing the arsenic standard from 50 to 10 microgram per liter at 21 to 30 deaths averted per year\textsuperscript{13}. 
For a drinking water standard expressed as a maximum contaminant level we identify the quantity $X - S$ as a measure of water quality, with implications for:
i) relative risks of different contaminant exposure, and ii) increased costs of meeting a particular standard. As stated succinctly by H. A. Thomas Jr. some forty years ago, "To set a standard is to impute a cost to benefit ratio."

### Hypothetical Example for Arsenic in a Drinking Water (microgram per liter)

<table>
<thead>
<tr>
<th>$X_{source}$</th>
<th>$S_{MCL}$</th>
<th>Treatment</th>
<th>$X_{final}$</th>
<th>$X_{final} - S_{MCL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>10</td>
<td>-15</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

$\uparrow$ $\uparrow$ $\uparrow$

$source \ quality \sim \Rightarrow costs \ final \ quality$

### Chemical Aspects of Contaminant Occurrence and Exposure

The chemical form in which a water contaminant exists in a supply governs its occurrence, transport, removal, and effects of exposure. Chemical processes on a watershed, in an aquifer, and in transport of source water to the place of treatment are aspects important in evaluating the nature and extent of contaminant exposure. The physical-chemical form, or speciation, is dependent on the overall ambient chemical characteristics of the source water, e.g., pH, dissolved oxygen, alkalinity, suspended particles, and organic carbon. Arsenic provides an example of the influences of ambient chemical composition. Arsenic
may exist in either the As (III) or As (V) oxidation state in water, depending on the oxidation-reduction balance of the water and sediments. Sediments often contain the reduced state of arsenic. Release to the surrounding water column can result in oxidation to the As (V) state as a result of bacterial action. As (V) is adsorbed to metal oxide particles in the water column. Adsorption is an important removal process for arsenic. The speciation of arsenic in a water supply is an important determinant of its transport and removal in aqueduct reservoirs and treatment processes. Treatment efficiencies for other adsorbed constituents in water may influence arsenic removal by adsorption-coagulation-filtration processes significantly. E.g., sulfate, humic substances, and phosphate. Oxidized versus reduced forms of a contaminant enter directly into present drinking water standards for nitrate and nitrite species. Among other contaminants in water, chromium, mercury, and uranium are elements with variable oxidized versus reduced speciation of potential importance to occurrence, removal, and nature of exposure. By water quality in general we imply not only the numerical values of standards expressed as maximum contaminant levels, but also an understanding of the chemistry, biology, and transport features which control exposure levels in each water supply.
Aquatic Ecosystems: Uses, Standards, and Protection

Safe drinking water means protecting the public health from harmful contaminants. Clean water concerns protection of fresh and marine waters for designated (beneficial) uses. A water quality standard for clean water is an ambient standard that applies to a specific water body, e.g., a river, a lake, or wetlands area. The water quality standard incorporates two key elements: 1) a description of the designated uses for the water body, and 2) a measurable quality criterion that must be met in order to support each designated use. Among designated uses are public water supply, fishing, wildlife protection, recreation, agriculture, industrial water, and navigation. Under these broad use designations, each State has the power to define more specific uses for a
particular ecosystem. Water quality criteria to support designated uses are
directed to six areas: aquatic life, human health, biological processes, nutrients,
pathogens, and wetlands. Clean water and safe drinking water, while protected in
two distinct U.S. legislative actions, are of course linked. Control of pollutants
from domestic and industrial point sources, and from non-point sources such as
agricultural runoff and acid deposition, is of benefit to protecting water supply
sources.

Quality standards for clean water appear highly complex when compared
with those for safe drinking water. Clean water quality criteria are based on
science and scientific judgment. Ambient standards for clean water protection
incorporate specific consideration of physical, chemical, and biological
characteristics of each water body. The geographical setting, aesthetic values,
and economic implications of designated uses must also be considered on a case-
by-case basis.

The U.S. Clean Water Act of 1972, and later amendments thereto17, calls
out 120 “priority toxic pollutants” (e.g., arsenic copper, cyanide, methyl bromide)
for which water quality criteria are required). In addition, there are 45 “non-
priority pollutants” (e.g., nitrate, phosphate, dissolved solids) requiring criteria.
In the area of aquatic life, for example, there are criteria for 23 toxic pollutants.
For human health there are 57 priority toxic pollutants.

A balance of photosynthetic and respiratory processes characterizes the
basic “health” of an aquatic ecosystem. The balance can be disturbed by
excessive discharge of municipal wastewaters (biochemical oxygen demand) or by nutrients for photosynthesis (nitrogen, phosphorus). Dissolved oxygen, chlorophyll a, and water clarity are valuable metrics for the basic condition of a water body. Beyond this, each water requires appropriate quality standards to protect its designated uses against effects of priority pollutants.

The path to water quality management currently followed in the U.S. to implement water quality standards for a water body is known as the **Total Maximum Daily Load Approach**. In brief, the concept is to “work backward” from the point in a water body where a numerical quality criterion must be met, toward the pollutant sources that determine that ambient quality. A classic application of this method entailed using the “oxygen sag equation” for a stream to compute the maximum allowable organic waste discharge rate from a point source, in order to attain a required dissolved oxygen level downstream.

Elaboration of this approach over the past fifty years has incorporated a wide variety of pollutants, hydrodynamic models, inter-media transfer processes and multiple sources of pollutants. A “matrix” for applying water quality standards represents uses, criteria, and modeled pollutant loading rates from point and/or non-point sources that satisfy the pertinent quality criteria.

### Hypothetical Example for Copper Water Quality in a Stream

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Stream use</th>
<th>Criterion function</th>
<th>CMC</th>
<th>Models</th>
<th>TMDL</th>
</tr>
</thead>
</table>
Copper | freshwater | aquatic life | 13 µg/l | dilution | 3 kg/day
--- | --- | --- | --- | --- | ---

| species | hardness=100 mg/l | chemical species |

Note a: In this simplified example the loading is computed from a flow model.

The criterion maximum concentration, the CMC, is total dissolved copper in the water. This value is a function of “hardness”, which is meant to represent Dissolved inorganic carbon (∼ HCO₃⁻) of the water. The underlying chemistry is: Cu²⁺ + HCO₃⁻ ⇌ CuCO₃(aq) + H⁺. The root toxicology criterion is based on free Cu²⁺. Note b: A completely fictional result, grounded in imagination!

It is easy to imagine that models relating water quality standards to total maximum daily loadings can become highly complex.

**The Infinitesimal Wrestle**

Abel Wolman remarked¹⁹ that over his lifetime he had progressed from measurements of parts per thousand, to parts per million, to parts per billion, to parts per trillion and had arrived at the threshold of parts per quadrillion. I think he accepted that trajectory as “his problem,” the engineer’s problem, possibly with some sense of resignation. He referred to smaller and smaller concentrations of water contaminants over time as the problem of the “infinitesimal.

Twenty-five years ago I was asked to consider the question: “Has our ability to detect pollutants in water outstripped our abilities to regulate and control?” At that time water quality engineers were faced with new challenges of removing volatile organic contaminants from drinking waters and controlling exposure to the newly found class of disinfection by-products. My response to
that question, in brief, was no. I suggested that the underlying physical and
chemical principles that had guided treatment research previously could be
relied upon to succeed with the newer contaminants. In particular I argued that
continuing advance in the science of environmental measurements was not the
problem the water profession faced, but was instead an essential part of any
solution. Health effects research, occurrence information, standards, and success
in treatment all require accurate and precise contaminant measurements.

Recently, Michael Kavanaugh\textsuperscript{20} wrote “When viewed with hindsight over the
past 40 years or so, the environmental profession has responded appropriately to
the technical and institutional challenges of emerging contaminants.” I believe
that is an accurate assessment. For example, the challenge presented by the
discovery of disinfection by-products thirty years ago has been met successfully
by research and development into mechanisms and new control technologies\textsuperscript{21}. I
think that lower levels of detection and methods for new contaminants
measurements in drinking waters are likely in the future.

**Zero and Measurable Numbers:** As of 2003 there are 77 chemical contaminants
or disinfection by-products for which drinking water standards have been set by
the U.S. Environmental Protection Agency. Twenty eight of these are
carcinogens. U.S. Public health goals for all carcinogens have been set at “zero”.
And what does “zero” mean? Reportedly, it does not mean 0.0, but represents
an “aspirational” goal or concept, as in *none* \textsuperscript{22}. 

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But Not in California: All of California’s drinking water public health goals are non-zero, and are set on the basis of scientific risk assessment. For example, for carbon tetrachloride, a carcinogen, the California goal is 0.1 microgram per liter. The maximum contaminant level is 0.5 microgram per liter. The lowest U.S. standard level for any contaminant in drinking water is that for “dioxin”, 30 picogram per liter (which corresponds to approximately 60 billion molecules of dioxin per liter of water). The analytical reporting levels for dioxin are between 1 and 10 picogram per liter. The detection level for dioxin is 5 picogram per liter. The California draft public health goal for arsenic is 4 picogram per liter, based on risk of lung and bladder cancer. The detection limit for reporting arsenic in water is now 2 microgram per liter.

Examples of Detection and Maximum Contaminant Levels

<table>
<thead>
<tr>
<th></th>
<th>10^-8</th>
<th>10^-6</th>
<th>10^-4</th>
<th>10^-2</th>
<th>1</th>
<th>mg per liter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Arsenic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dioxin</td>
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</tbody>
</table>

Measurements and Technology Are Both Needed: It is essential to be clear about the distinctions between concentrations of contaminants that are “zero”, “detectable,” or “measurable.” It has been proposed recently that the policy of establishing risk-based drinking water standards to protect public health should
be set aside and replaced by a policy requiring the best available technology to “minimize the concentration of all pollutants”\textsuperscript{23}. This strikes me as a vague objective. I question if the overall health risks from drinking water contaminants would be predictably less or greater under such a policy. In earlier times it was proposed by some that all organic pollutants be lowered to the detection level by treatment innovations. By definition, that policy would have as an objective to lower contaminant concentrations below prevailing maximum contaminant levels. Risks would then decrease, but in an unpredictable way if monitoring of individual contaminants is abandoned. Technology costs would surely increase. It seems evident that we would be accepting less information about benefits and costs, if a defined water quality were to be replaced by a best available technology policy. I believe that we need both sustained measurements of water quality, as well as innovative engineering approaches to achieving water quality standards.

\textbf{CODA}

\textit{Water quality is a comparison. Natural waters vary widely in chemical composition, e.g., alkalinity, pH, mineral content, dissolved organic carbon, and degree of contamination from human activities. Public health and the health of aquatic ecosystems each require knowledge of the effects of exposure to contaminants. By water quality we imply a comparison between the effect requirements and the actual properties of particular waters for uses in water supply or the protection of natural waters. These properties span a large set of chemical, biological, physical and aesthetic parameters. The array that characterizes water quality thus comprises water uses, actual water properties, and required water properties. Progress in water quality demands advances in the science of exposure and effects, the science of measurement, and the sciences underlying water source management and control technology. Progress also demands water quality standards with force of law to close the }
gap between required and actual water properties. We should also not forget that perceptions of water quality and the human values attached to water are still important.

References and Notes