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# WHOLESOME AND PALATABLE DRINKING WATER: A BACKGOUND PAPER ON WATER QUALITY ASPECTS OF WATER SUPPLY

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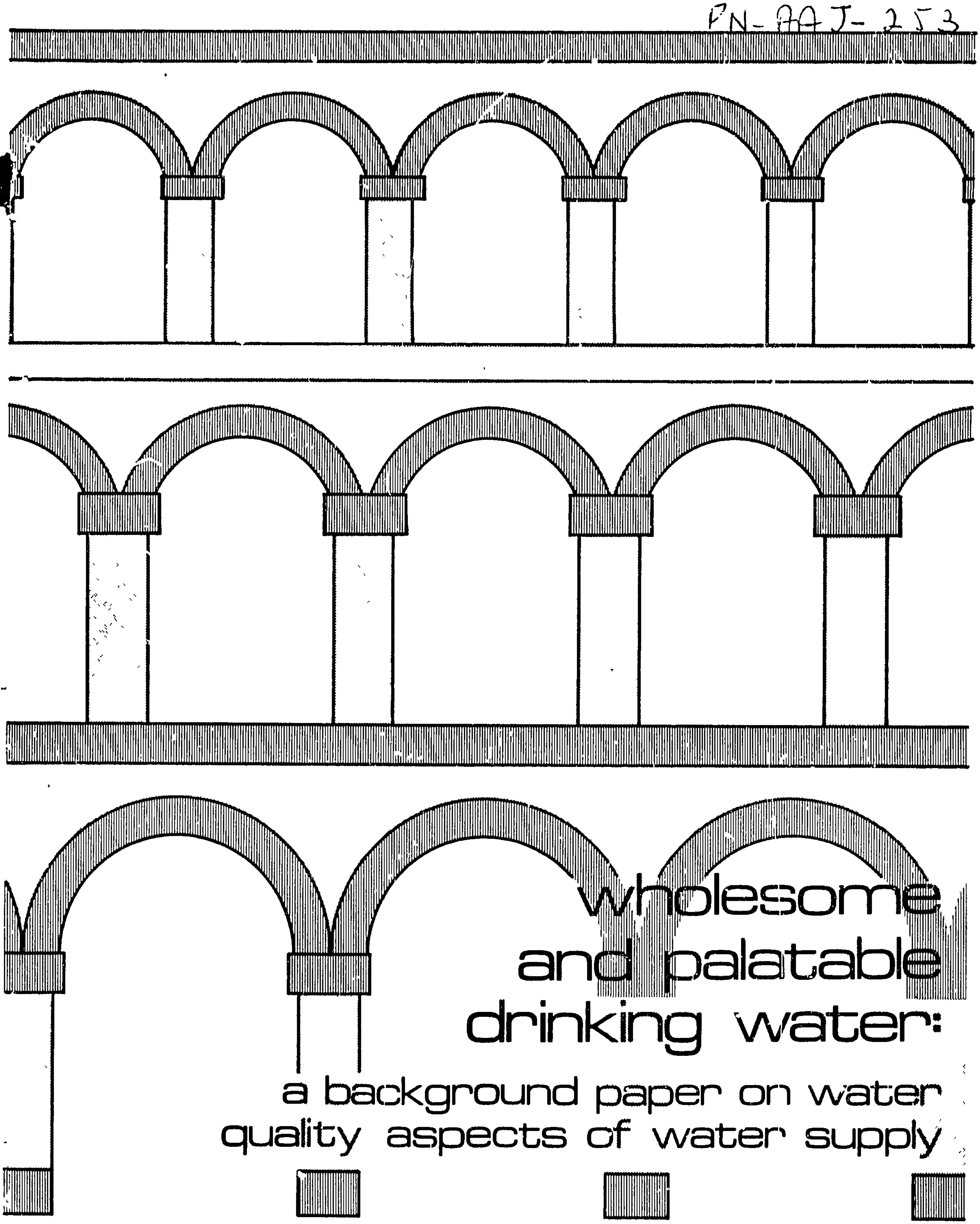

# wholesome and palatable drinking water:

## a background paper on water quality aspects of water supply

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# WHOLESOME AND PALATABLE DRINKING WATER: A BACKGROUND PAPER ON WATER QUALITY ASPECTS OF WATER SUPPLY

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# SUMMARY AND CONCLUSIONS

The objective of this paper is to provide background discussions of water quality aspects of water supply, emphasizing small domestic water supplies serving dispersed rural populations in developing countries.

Judgments about the wholesomeness and palatability of drinking water have since antiquity been based on the clarity, the taste and odor, and the source of the water. The sanitary survey and water quality constituent standards as bases for assessing quality evolved in and consequently were shaped by a society experiencing multiple transformations: urbanization, industrialization, and centralization. From about 1870 through 1913, the sanitary survey provided the primary basis for evaluating water quality. Laboratory analyses provided corroborative and supplementary evidence about contamination. Although first proposed as professional guidelines for interpreting laboratory analyses, standards became subsequently the predominant basis for assessing quality. Standards serve variously as goals, normative levels, and regulatory limits(and consequently, also as design specifications.

Formulating constituent standards poses a complex of administrative, statistical, scientific, and technical problems. Clinical or epidemiological evidence alone seldom indicates the appropriate level because of inherent statistical uncertainty in the studies and incomplete knowledge of the behavior or action of the pathogen or toxic agent. Commonly, these data must be supplemented by knowledge of the availability and cost of treatment methods, plausible assumptions, the number and culture of the people at risk, and local tastes.

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The evolution of chemical and(later)bacterial indicators of fecal contamination reveals the conflicting demands of increased specificity(so that *only* fecal contamination will be detected) and of extreme sensitivity (so that *all* fecal contamination will be detected). Novel indicators do not avoid these conflicts. The meaningful interpretation of either sanitary survey observations or laboratory analyses requires a well-trained technical staff.

Where groundwater is available and not chemically contaminated or where surface waters require clarification, compliance with existing W.H.O. or other bacterial standards seldom entails substantial further investments. However, where chemical contamination is present or where logistic problems (e.g., chemical production or delivery) block compliance, rigid adherence to regulatory standards alone may require considerable incremental development costs. Epidemiological data, alternative sources, and other local conditions should be taken into account on a case by case basis.

But because of the technologically irregular relationship between treatment and other development costs and the resulting water quality and because alternative designs simultaneously alter several aspects of water quality, design decisions are not always sensitive to changes in water quality standards. Uniform application of a single set of constituent standards may produce undesireable patterns of investment. The practical importance of such misallocations can only be assessed at a regional or national level.

# I. INTRODUCTION

## *General Focus*

The purpose of this paper is to provide background material on water quality aspects of water supplies for an expert panel developing water quality guidelines for the United States Agency for International Development activities related to the World Water Supply and Sanitation Decade. More specifically, this discussion paper shall principally consider water quality aspects of small domestic water supplies serving dispersed rural populations in developing countries.

However, "dispersed" and "rural" do not appear to have universally or even widely accepted definitions. By domestic water supply, we intend to include household water use for drinking, cooking, and washing and to exclude waste removal, irrigation, and other uses. Definitions of "rural" water supplies reviewed by Saunders and Warford (1976), although rather varied, all certainly encompass villages with populations less than about 3000 persons where agricultural work predominates. The rural areas studied by White *et al.* (1972) had population densities ranging from about 30 to 700 persons/Km$^2$ with an average of about 200. The lower end of this range would undoubtedly be classed as a "dispersed" population.

According to 1970 estimates reported by Saunders and Warford (1976), well over one billion persons in developing countries are covered by this definition but only about 14 percent have "reasonable access to a safe water supply". Obviously, the remaining 86 percent currently have access to some source of water — frequently in meager quantity and of poor quality — or they would soon die.

As stressed by Bradley (White *et al.*, 1972) in his classification of health hazards associated with water supplies, the quality and the quantity, and the location of available water influence the health of the user population. Water quality is most important where water-borne diseases such as typhoid fever, cholera, paratyphoid, hepatitis, and the varieties of gastroenteritis are of principal concern. In contrast, water washed diseases such as trachoma, conjunctivitis, and dermatitis are less sensitive to water quality improvements than to increases in water availability. Finally, water supply influences water-based diseases (e.g., schistosomiasis and guinea worms) and water-related diseases (e.g., malaria, onchocerciasis, and trypanosomiasis) mostly via its location and the resulting opportunity of exposure. This paper will primarily address questions of water quality influences on water-borne disease.

This emphasis does not imply that water quality is of more critical concern than either the water quantity available, the supply location, or sanitation practices. Clearly, a supply of high quality that only provides each person a few liters per day or that results in greater exposure to malaria , schistosomiasis, or guinea worm cannot be considered satisfactory. Nor does this emphasis imply that it is more difficult to meet the quality requirements of a water supply than the quantity or location requirements.

*Specific Objectives*

With the above limitations, we will examine a series of questions in the course of the discussion to follow:

1. How have and do professionals establish the wholesomeness and palatability of water supplies?
2. How have standards been developed and applied? What complications are involved?
3. What other tools have been used to assess water quality?
4. Have standards and other tools provided effective means for reducing water-borne disease?

These questions will be addressed throughout the sections below. First, the historical development in Great Britain and North America of the concern with and the means for assessing the quality of water supplies will be reviewed. This focus mirrors both the pioneering role of Great Britain in Sanitary Reform and the availability of source materials in English. Second, the contemporary professional techniques will be surveyed and evaluated. Next, the problems of implementing/applying these tools in rural areas of developing countries will be outlined. Finally, the issues of water quality and availability will be explored in the context of trade-offs implicit in program designs.

Each of these sections is predominantly the work of a single person and addresses distinct facets of water quality questions. Although we have attempted to eliminate or avoid repitition, some recapitulation has been necessary to provide clarity and continuity in the arguments presented.

Two appendices accompany the paper: Appendix A contains the bibliography for all sections and Appendix B summarizes past and present drinking water standards. Appendix B outlines by example the evolution of current standards, providing supplementary reference material for sections II, III, and IV.

# II. HISTORICAL DEVELOPMENT

## *Introduction*

The historical development presented here centers almost wholly on urban experience in Europe and North America during the last two hundred years since it was in that context that current tools for assessing water quality evolved. Although there are many similarities between Europe and North America in the period from 1750 to 1900 and the developing countries today, substantial differences also exist as Rybczynski *et al.*, (1978) have pointed out. The regions differ in both the quality and quantity of available water resources and in the governing conditions, especially population size and growth rate, climate, important endemic and epidemic pathogens, economic and social organization, and the resources available. Since our focus is ultimately to be rural water supply, the urban thrust of water supply experience in Europe and North America additionally limits the relevance of that experience here.

Despite these very real dissimilarities, the techniques for assessing the wholesomeness and palatability of drinking water did evolve in the liberal industrializing nations of Nineteenth Century Europe and North America. So long as we avoid treating the tools developed in that context as final or universally applicable, examining that historical development should clarify contemporary issues and not lead us astray in analyzing those tools.

To that end, we will review, in turn and then in overview, 1) the practice in assessing drinking water quality in the pre-industrial world, 2) the events of the Great Sanitary Awakening in Nineteenth Century Great

Britain, 3) the successes and failures of public health boards in the U. S. at the turn-of-the-century, 4) the promulgation of the 1914 U. S. Treasury Department Standard and the resultant professional response, and 5) the several revisions and expansions of the 1914 U. S. Treasury Department Standard.

### *Pre-Industrial Practice*

Baker (1948) suggests that the *Sus'rata Samhita*, a Sanskrit collection of medical lore which probably dates from c. 2000 B.C., contains the first recorded distinction between pure and "foul water", with recommendations for purification methods. However, the recognition that some waters were better than others for drinking and cooking is undoubtedly considerably more ancient. The available records and remains of the civilizations of the Nile, Tigris-Euphrates, and Indus river valleys and of Crete and the Inca indicate emphasis on hygiene,cleanliness, and water supply (Rosen, 1958; Baber 1948). In addition, pre-literate hunter and gatherer cultures apparently prefer some waters over others (Lévi-Strauss, 1966).

In Airs, Waters, and Places (Lloyd(trans.),1978), the Hippocratic writers discuss selection of the most wholesome sources of water supply and the relation between water supply and disease. They rank water sources in order of suitability for drinking water: "The best are those which flow from elevated grounds, and hills of earth; these are sweet and clear... ." "Such waters then as are marshy, stagnant, and belong to lakes ... lose their proper color, are unwholesome and form bile... those who drink them are very subject... in the summer to dysenteries, diarrheas, and quartan fevers....". Further, waters that "... are salty, crude, and harsh, are not good for drink". Finally, in the *Aphorisms*, the Hippocratic writers pragmatically suggest that "... drink which is slightly worse, but more palatable, is to be preferred to such as are better but less palatable".

Although the Greeks had in some cases brought water from considerable distances into their cities, the Romans developed an extensive system of aqueducts that provided Rome an abundant supply of water. Frontinus ( 97 ) chronicles the evolution of this system and reveals a concern with the quality of the supplied water, principally with its palatability, color, and clarity.

Near contemporaries of Frontinus, Vitruvius Pollio and Pliny describe methods of testing the quality of water for domestic supply (Herschel, 1913). Hardness, sediment, surface scum on boiling, and taste and odor were of specific interest, but the over-riding criterion was the health of the people who customarily consumed it: if they were healthy, it was good to drink.

## *The Industrial Revolution, Liberalism, and the Great Sanitary Awakening*

The idea that filth and disease are associated was not novel in the early Nineteenth Century. The idea that public works projects to remove the filth could and should be undertaken specifically to improve health *was* novel. The resulting sanitary reform movements were widespread in the first industrializing nations (Rosen, 1958). But it was in the vanguard of the new industrial nations, Great Britain, that the issues of the movement were first clearly defined.

During the first half of the Nineteenth Century, Great Britain experienced several fundamental transformations. Parlimentary reform in 1832 deposed the "Squirearchy" that had been in control since the Glorious Revolution of 1688 had affirmed the ascendancy of landowners. Production and distribution processes were transformed by the construction of railroad and canal systems, expansion of markets, development of precise tools, the availability of steam power, and the creation of a mobile population of wage-earners. Jointly described as the Industrial Revolution, these changes centered on the textile industry in Great Britain. Consequently, centers like Manchester exploded from 24,000 persons in 1773 to about 300,000 by 1830, but were neither represented in Parliament nor governed effectively by local institutions.

Urban services were commonly provided by private companies in keeping with the recently enunciated precepts of political economy. Where water was provided by distribution systems, private companies were in control. Elsewhere, water was drawn from wells, pumps, springs, and streams.

In the reformed response, Parliament passed a succession of reform acts: 1833, Factory Bill and Slavery abolition; 1834, The New Poor Law; 1836, Registration of Births and Deaths Act; 1835, Municipal Corporations Act. These and other reforms that created the institutional and legal framework necessary for capitalism were inspired in large part by the writings of Jeremy Bentham. Although the number of his disciples, the Philosophic Radicals, in the reformed Parliament was relatively small (Thornton, 1975), many of the reforms, especially the New Poor Law, were closely patterned after sections of Bentham's *Constitutional Code.* His writings reflected both an insistence on order, efficiency, and social discipline and a concern with social conditions: the rising Middle Class ethos (Rosen, 1958).

As one of its first actions, the reformed Parliament had set up a Royal commission to investigate the existing parish-administered poor law and to propose reforms. On the recommendation of one of the Commissioners (Nassau Senior), the former secretary of Bentham, Edwin Chadwick, was made assistant commissioner. The 1834 Report of the Poor Law Inquiry, jointly authored by Chadwick and Senior, argued for a new law close to what had been suggested by Bentham (Zagday, 1948).

Chadwick stayed on as the Secretary to the newly established Poor Law Board. Based on the earlier Inquiry and subsequent experience, Chadwick and the Board came to believe that filth and disease were related and that substantial social and economic costs resulted: lost labor, medical costs, burial costs, and support for survivors (Rosen, 1958).

Drawing upon reports on conditions in each of the Poor Law Districts and on data provided in accordance with the recent Registration Act, Chadwick prepared the epochal *Report... on an Inquiry into the Sanitary Conditions of the Labouring Population of Great Britain* (1842). Sufficiently radical for the Poor Law Commissioners to refuse to endorse it, the *Report* outlined both a plausible epidemiological theory based on the miasmic theory of disease and the practical institutional and engineering means to reduce the disease. He concluded that:

1. Disease, especially communicable disease, was the result of lack of drainage of water supply, and of refuse removal.
2. Public health problems are fundamentally engineering rather than medical problems.
3. Efficient and consistent application of available engineering knowledge and techniques could economically reduce disease.

These arguments for public investment in drainage, water supply, and refuse removal were utilitarian rather than humanitarian. John Simon, the first Medical Officer of London, argued, "Sanitary neglect is mistaken parsimony. Fever and cholera are costly items to count against the cheapness of filthy residence and ditch-drawn drinking water" (Rosen, 1958).

The visions and insights of the *Report* which provided the blueprint for public policy for the next 50 to 60 years become even more remarkable since they were based on the miasmic theory of epidemic constitution -- epidemics are caused by the constellation of weather conditions and local circumstance. In the words of Southwood Smith, another Bentham disciple, "The immediate or exciting cause of fever is a poison formed by the corruption or the decomposition of organic matter... [which] give off a principle... [which] produces the phenomena constituting the fever" (Rosen, 1958). By the early 1800's, the miasmic theory was almost universally accepted. The most respected scientist of the era, Liebig, supported the theory, equating the miasmas with gases rising from rivers polluted with sewage (Kargon, 1977).

In opposition to the miasmic theory, Henle in 1840 restated in modern form the contagion theory of disease that had been first systematically formulated by Fracastoro in 1546. But it was John Snow and William Budd who provided sound epidemiological evidence that cholera was communicated via drinking water contaminated by the fecal material from an infected person and not by miasmas. Although the evidence from the Broad Street Pump incident was ambiguous, Snow's (1855) energetic investigation of mortality differences between populations served by different water supplies clearly demonstrated the importance of water supply. (It is notable that many patients interviewed by Snow attributed their illness to the water.)

Although the theories differed, Snow (1855) proposed preventative remedies similar to Chadwick's: 1) provide good drainage, 2) provide water supply free of sewage contamination, 3) improve housing. But the proposed measures for epidemics differed considerably. Snow recommended: 1) boil all water before using; 2) wash all food, and steam, boil, or fry it; 3) isolate the sick; and 4) quarantine ships. (It is perhaps coincidental that quarantine, antagonistic to the free trade concepts of Liberalism, was rejected by holders of the miasmic theory as unreasonable and uneconomic (Rosen, 1958).)

So by 1860, the foundation and the basic principles had been laid out for subsequent public health work. At the core was the provision of a water supply free of contamination from sewers, cesspools, and house-drains. Chadwick (Jones, 1929) also stressed the importance of making supplies convenient: "The interposition of the labour of going out and bringing home water from a distance acts as an obstacle to the formation of better [hygienic] habits". The definition of wholesome had become both more concrete and more subtle.

### *Public Health Boards and the Sanitary Survey*

One of the major institutional responses to Sanitary Reform was the public health board. Local boards had previously been established in cities such as Boston, Edinburgh, and Glasgow, commonly in response to an epidemic and often becoming inactive afterwards. The first national or state board was mandated by the Public Health Act of 1848 in Great Britain in response to the cholera epidemic of 1848 (Rosen, 1958). The General Board of Health was patterned after the Poor Law Commission. Local boards were also established either by local petition or by mortality criteria and had authority over water supply, sewerage, and sanitation.

With Benthamites Chadwick, Lord Shaftesbury, and Southwood Smith as commissioners, the General Board exhibited strong centralizing tendencies that appeared dictatorial to many. Editorials in the London Times suggested that "... we prefer to take our chance with cholera and the rest, than be bullied into health" (Marston, 1925). The act mandating the board was not renewed in 1854 and an era ended as Chadwick retired from official life. The duties of the General Board were eventually transferred to the Privy Council until the Public Health Act of 1875 re-established the Board.

In the United States ten state health departments were established between 1869 and 1877. The first effective board was formed in Massachusetts in 1869. In large part, the Board membership followed the pattern proposed by Shattuck (1850) nineteen years earlier: three physicians, a lawyer, a civil engineer, an historian, and a businessman. Although advisory and cooperative rather than regulatory in function, the Board was responsible for ". . . the examination and investigation of public water supplies . . ." (Whipple, 1917).

By the 1870's, there had come to be general agreement that drinking water contaminated by sewage was dangerous to health, although the germ theory of disease was still disputed (Rosen, 1958). Precisely how the extent of or freedom from contamination was to be established was not clear. In Massachusetts and Great Britain, boards relied heavily on field investigations or sanitary surveys to evaluate water supplies. From 1875 to 1880 alone, the Massachusetts Board carried out sanitary surveys of eleven watersheds (Whipple, 1917).

Public and private sanitary surveys had been used from the late 1700's to investigate problems and provide a basis for remedial action. In addition to Chadwick's Report of 1842, Shattuck (1850) had developed and justified a detailed plan for a sanitary survey of Massachusetts, Griscom had in 1848 published a sanitary survey of New York, and Kay, Engles, and Southwood Smith had incorporated sanitary surveys into broader social analyses (Rosen, 1958). Sanitary surveys had been the responsibility of district health inspectors for the British General Board (Flinn, 1968).

In condemning the London water supply companies in 1850, the General Board cited as evidence pollution by sewage, hardness, organic matter and the lack of filtration and high pressure delivery (Jones, 1929). A district health inspector to the board weighed clarity, hardness, and the presence of "filth" in assessing quality (Flinn, 1968).

Later, Rafter (1889) recommended that sanitary surveys or in his words, "environmental examinations," consider basin topography, geology, population, industrial activities, and pollution sources and include a comparative study of a similar but unpolluted basin. At about the same time in Great Britain, Fox (1886) stressed the importance of knowing 1) the source of the water (i.e., is it a spring, well, stream . . .?), 2) the depth, if it is a well, 3) the surrounding geological and soil characteristics, and 4) the distance from the source to pollution sources.

The first consulting chemist to the Board, Nichols (1878) regarded the problems of clarity, color, and hardness as remediable but that water supply contamination ". . . by an admixture of substances known or generally suspected to be injurious . . . should be rejected at once as a source of domestic supply." Stearns and Drown (1890) later recommended that pollution should be assumed ". . . when the population upon the drainage area is more than 300 to the square mile." Ten years later, Sedgwick (1902) summarized the ". . . most advanced ideas" for establishing and conserving the "purity of surface waters":

1. Secure a supply of high organic purity.
2. Keep the watershed as thinly populated as possible.
3. Provide extensive storage.

In all it appears that the Board relied principally on the presence or absence of known or suspected contamination and to a lesser extent on impoundment (storage) and treatment in evaluating water supplies.

In addition to field investigations, laboratory analyses both of the chemical and of the biological characteristics of waters were also employe in evaluating water supplies.

Chemical analyses had been run during the debates surrounding the introduction of public water supplies into cities in the early Nineteenth Century (Blake, 1956) and had been used by Snow (1855) to distinguish water supply companies. Whereas the early analyses provided mostly inorganic salt concentrations (Whipple, 1917; Blake, 1956), recommended tests for "sanitary chemical analysis" generally included clarity, color, odor, total solids, volatile solids, chlorine, free and "albuminoid ammonia," nitrite and nitrate, hardness (both temporary and permanent), magnesium and sulfate levels, "oxygen required," and, in some cases, metals (Fox, 1886; Rafter, 1889; Drown, 1892). Some tests were rather imprecise (± 10 mg/l) but the greatest problem was in interpreting the results.

Even the earlier chemical analyses invited more than one explanation: Was the high mineral content of a New York well the result of contamination from graveyards and privies or of seawater intrusion? (Blake, 1956). In contrast to analysis for a single, specific substance, the results of a sanitary analysis, according to Drown (1892), must consider the locality and surroundings, the season, the sample position, and other factors. Revealingly, Fox (1886) reports a study in which several samples from the same well were sent to five different analysts—opinions ranged from "unusually pure" to "unfit for drinking." With such disparate opinion, Fox (1886) observed, "It would be a great convenience to the analyst if he were able to appraise each determination at its true value in a definite manner, which can be represented in figures."

Consequently, it is not surprising that many sets of numeric guidelines were proposed after 1875. Some, such as Leeds (Rafter, 1889), provided fixed limits for the acceptable chemical composition of river waters in the U.S. In contrast, Fox (1886), Dupre and Hehmer (1883, quoted in Fox (1886)), and others argued that district or local standards were superior to general standards since the fitness of a water for drinking purposes is best judged ". . . by its conformity to, or divergence from, the general characters of the waters of the district . . . which from their surroundings may fairly be taken as unpolluted." Fox (1886) tabulates "typical" analyses of "good water."

Drown's development in the 1880's of excess chlorine as an indication of fecal contamination essentially generalized the idea of district or local standards (Whipple, 1917). "When the amount of chlorine is in excess of the normal, the amount of this excess expresses the extent to which the water is believed to have been polluted" (Drown, 1890 in Whipple, 1917). Keeping in mind that the excess above normal "does not necessarily imply present pollution," Drown proposed an approximate conversion between observed excess chlorine and population density: $\sim 21$ persons/ $mi^2/0.1$ mg/l chlorine differential from normal.

Frankland based his interpretations primarily on Carbon to Nitrogen ratios and organic carbon content; the higher the C:N ratio the less likely it was that the organic matter present was of fecal origin (Fox, 1886). Wanklyn, instead, based his interpretations on "albuminoid ammonia" and free ammonia levels (Fox, 1886). According to Rafter (1889), "The ammonia process has by common consent come to be regarded as the most satisfactory chemical determination of the sanitary value of potable water. . . ." Based on studies of polluted wells, Wanklyn proposed 0.15 mg/l albuminoid ammonia as the high permissible limit.

But as Rafter (1889), Drown (1892), Fox (1886), and others point out, considerable sewage pollution may be generally associated with high albuminoid ammonia levels but high levels do not necessarily imply sewage pollution: high levels may be from "vegetable growths." Except for the case of metals, Fox (1886) is unwilling to draw blanket conclusions about safe levels. Both Fox (1886) and Drown (1892) take special care to discuss non-fecal sources of albuminoid and free ammonia, $NO_2^-$ and $NO_3^-$, and other chemical indicators.

To avoid attaching too much significance to single or a limited number of parameters, Wigner and others (Fox, 1886) developed water quality indexes that weighted individual results. Fox (1886) suggested modifications that made consideration of certain parameters conditional on the levels of others. The rules for interpreting the overall index specified what scores corresponded to exceptionally pure, First Class, Second Class, or undrinkable water.

Much of the chemical analyses were direct and indirect estimates of organic matter concentrations since the miasmic theory of disease was still supported in modified form by some into the 1890's. In the 1871 annual report of the Massachusetts State Board, von Pettenkofer's analysis of the causes of typhoid fever were reviewed: English opinion that cholera and typhoid were the result of fecal contamination was accepted but the causal factor was held to be the decomposition of organic matter and not the presence of "germs." (Whipple, 1917; Farlow, 1879).

The "germ"(or zymotic, or ferment) theory of disease, promoted by Pasteur and Lister and opposed by Liebig and von Pettenkofer, was rigorously demonstra by Koch in 1876 for anthrax by applying criteria proposed by Henle thirty-six years earlier. By the turn of the century, the microbial basis for typhoid, cholera, bacillary dysentery, and many other diseases had also been demonstrated (Rosen, 1958). The 1888 annual report of the Massachusetts State Board contained a report by Tucker applying the germ theory (Whipple, 1917). Two years later, Mills (1890) stated, "Typhoid fever is . . . now generally attributed to . . . the typhoid bacillus."

With the realization that diseases were the result of specific microorganisms and not of gases arising from decomposing organic matter, microbiological studies assumed more importance. Earlier, workers had realized that "Chemical analysis is not alone sufficient to detect impurities in water for an incredibly small amount of the poison of typhoid fever or cholera is sufficient . . ." to cause the disease (Windsor, 1876 in Whipple, 1917). But, early studies were limited to microscopical examinations. Sedgwick (1890) reviewed the early work, including studies of Hassall used by Snow (1855). Once workers (Rafter, 1889; Nichols, 1878) had become convinced that although algae might be responsible for taste and odor problems and for reduced filtration runs they did not ". . . communicate any unwholesome quality to the water," attention became fixed on bacteria.

Angus Smith apparently was first (c. 1876) to apply the solid media methods of Koch to the problem of detecting fecal contamination (Fox, 1886), but Frankland, Miquel, and others (Fox, 1886; Prescott and Winslow, 1915) also actively experimented with different bacteriological methods prior to 1890. In the 1890's, Theobald Smith, George Fuller, and Stephen Gage on the technical staff of the Massachusetts State Board and many elsewhere began to use the variations of the plate count and the liquid media enrichment methods for <u>Bacillus coli</u> (isolated by Escherich in 1885) to investigate stream pollution, to evaluate filtration and disinfection efficiency, and to detect fecal contamination (Whipple, 1917; Prescott and Winslow, 1915). To assure reliability and comparability standardization of methods was proposed in 1895 (Prescott and Winslow, 1915). It was clear by 1898 that bacterial tests were much more sensitive than chemical tests (Klein and Houston, 1898).

In applying them to detect fecal contamination, problems of interpretation arose. Both Miquel and Sternberg (Prescott and Winslow, 1915) proposed graded scales of sanitary quality based on the 20°C gelatin plate counts. In 1892, the German Imperial Board of Health set forth a treatment standard that required all water purification plants to produce a finished water with less than 100 bacterial/ml based again on the 20°C gelatin place count (Baird, 1913). But problems with interpreting the plate counts so straightforwardly were soon recognized. Fox (1886) discussed the "difficulties in judging as to the sanitary condition of a water from an estimation of the number of colonies developed." He suggested that:

> It is undoubtedly true that the biological is the most delicate of all known tests, and that the purer the water, _ceteris paribus_, the smaller the number of colonies present. It is equally true, however, that microorganisms are to be found in nearly every water, and that length of storage, temperature, degree of aeration . . . which have much to do with the number of colonies present, have, of course, no necessary connection with pollution.

As with albuminoid ammonia and chlorine, there were reasons for high plate counts other than fecal contamination.

Given the number of rival tests it is remarkable that every discussion of how to interpret either chemical or bacteriological analyses the importance of collateral field investigations was emphasized. Fox (1886) held that "the history of a water, its surroundings, and the knowledge of the geological formation from which it is obtained must . . . (bear) on the judgment of the analyst," and that "it is a golden rule in water analysis never to give an opinion . . ." unless field data are available. Rafter (1889) cautioned that "the results of chemical analysis must conform and explain the facts gathered by personal inspection." Drown (1892) also insisted that proper interpretation required knowledge of locality and surroundings, season, and others.

By the first decade of the Twentieth Century, U.S. urban typhoid mortality rates were less than a third the level of twenty-five years before, in part as the result of public health board actions and better water supplies. The realities and illusions of the improvements will be discussed later. Chemical tests were by then not run to detect fecal contamination but to measure lead, copper, iron, chloride, turbidity, color, taste/odor, hardness because of toxicity or palatability interests (Mason, 1912; Johnson, 1913; Fuller in Johnson, 1913). Some earlier popular indicators had fallen into disrepute: ". . . a great deal of time is wasted in many laboratories in the determination of free and albuminoid ammonia, nitrites, and nitrates" (Winslow in Johnson, 1913). There remained efforts to develop local or normal standards (in distinction to absolute or "universal standards of purity") to permit the results of water analysis to be conveniently interpreted in ". . . reaching conclusions regarding the wholesomeness of waters" (Bartow, 1908). In the Illinois standards typical chemical compositions for uncontaminated waters from Lake Michigan, streams, shallow wells, and deep wells are tabulated (Bartow, 1908).

Notably, the Illinois standards included typical values for 20°C gelatin plate counts and for "colon bacillus" enrichment tests (Bartow, 1908). The use of bacterial indicators of fecal contamination was quite general by 1913: They were used to assess filtration efficiency, to detect pollution of wells by cesspools, and to monitor stream pollution. Bacillus coli was accepted as the "surest index of sewage pollution" available, providing not an absolute guarantee of the absence of pathogens but instead a relative measure of the chance of exposure (Johnson, 1913).

Two respected sanitary scientists, George Whipple and W. P. Mason, addressed the problems of assessing water quality in this period.

Mason held that absolute ". . . standards for the interpretation of analytical results" are impossible to set forth (Mason, 1905; 1912). Instead, "A water analysis . . . is a series of experiments" and examinations carried out as the basis for forming an opinion, ". . . as does the medical practioner frame his diagnosis" (Mason, 1905; 1912).

The final opinion should be based on a sanitary survey and on comparison of chemical and bacteriological results with local "normals." Mason emphasized the diagnostic value of Bacillus coli determinations (especially in measuring filtration efficiency and in tracing sewage), but was cautious in proposing guidelines for its use in detecting contamination. Although he considered the persistent detection of B. coli in 0.1 ml samples as sufficient to condemn the water and persistent detection in 1 ml samples as evidence of fecal contamination, he was concerned that "many excellent water supplies . . . would have to be condemned if we were to insist on the absence of B. coli from 10 ml samples." (Mason, 1912)

Whipple (1907) observed that because of the many attributes involved and their variations in importance, it is difficult to frame a definition of pure and wholesome water in "positive scientific terms." Where such definitions are necessary, it is generally specified what ". . . foreign substances shall not be present, or in what amounts they are permissible, instead of defining the positive qualities which the water shall possess" (Whipple, 1907). In all cases, that should include freedom from poisonous substances, pathogens, and fecal bacteria and depending on local preference a practically clear, colorless, and odorless water free from objectionable taste. Such demonstration requires both laboratory and field inspection.

The recommendations of Mason and Whipple do not distinguish between treated and untreated or "raw" waters. But by 1913, as Johnson (1913) points out, the true concern was with the treated waters, where filtration and disinfection could produce greatly reduced bacteria levels. In addition, contracts between water companies and municipalities specified, generally in vague terms like "pure and wholesome," the required finished water quality (Johnson, 1913). Although a Mississippi jurist argued in 1904 that "Any mortal knows whether water is fit to drink and use" (Mason, 1908), no concrete guidelines for acceptable design and operation of treatment plants existed. Baton (Johnson, 1913) compared current ambiguous water quality specifications with ". . . specifying a steel for structural purposes as strong and serviceable." Similarly, Milligan (Johnson, 1913) tentatively proposed a quantitative description of purity based on measureable quantities like turbidity, color, and total bacteria counts. The definitions of wholesome and palatable were becoming more complicated and more numerical.

## The Treasury Standard and Professional Response

In January 1913, the Secretary of the Treasury promulgated by authority of the Interstate Quarantine Acts of 1893 and 1897 a regulation requiring certification of the water supplies of railroads and ships involved in interstate commerce. On 14 January 1913, the Secretary appointed a "commission of fifteen sanitarians to recommend a standard of purity for railroad and ship water supplies."

Since the Secretary provided no explanation for the new regulations, we can only speculate about the motivations. Urban water supplies were in 1913 supervised by state health boards that might or might not have specific performance standards, by city boards with or without local standards, by contractual obligations with or without quantitative quality specifications, or were unregulated and may or may not have had plant standards. Quality obviously varied considerably between supplies. Since variations in analytical technique cloud comparisons among cities, the analyses tabulated by Bartow (1915) on about 100 samples obtained from trains of many origins provide a rare basis for evaluating variations in quality. Some of the samples were extremely poor: 7% had more than 200 mg/l hardness; 25% had more than 1000 bacteria/ml (37°C agar plate), and 8% produced positive Bacillus coli reactions in all 5 of the 10 ml samples, implying a most probable B. coli concentration considerably above 10/100 ml (Bartow, 1915). However, many were of much better quality: 34% had hardness less than 50 mg/l; 40% had 37°C agar plate counts below 50/ml; and 37% had no positive B. coli reactions in any of the five 10 ml samples.

Other national and international standards were also discussed in 1913 and 1914. A chemical and bacteriological standard for bottled water was issued by the Department of Agriculture, specifying less than about 2 B. coli/100 ml* (Hinman, 1920). In 1914, the U.S.-Canadian International Joint Commission established standards for both raw and finished waters (Fuller, 1915; AWWA, 1936). In the Fall of 1914, a committee of thirteen bacteriologists and sanitarians appointed by the Royal Institute of Public Health in Great Britain refused to "lay down any fixed standards" but did suggest that waters containing less than

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*Except where indicated, all B. coli results reported as X% positive of the Y ml sample tubes have been converted to MPN/100 ml by the following equation:

$$\text{MPN} = \frac{-230.3}{Y} \quad \log_{10}\left(1 - \frac{X}{100}\right)$$

about 0.3 B. coli/100 ml were of "good" quality (Fuller, 1915).

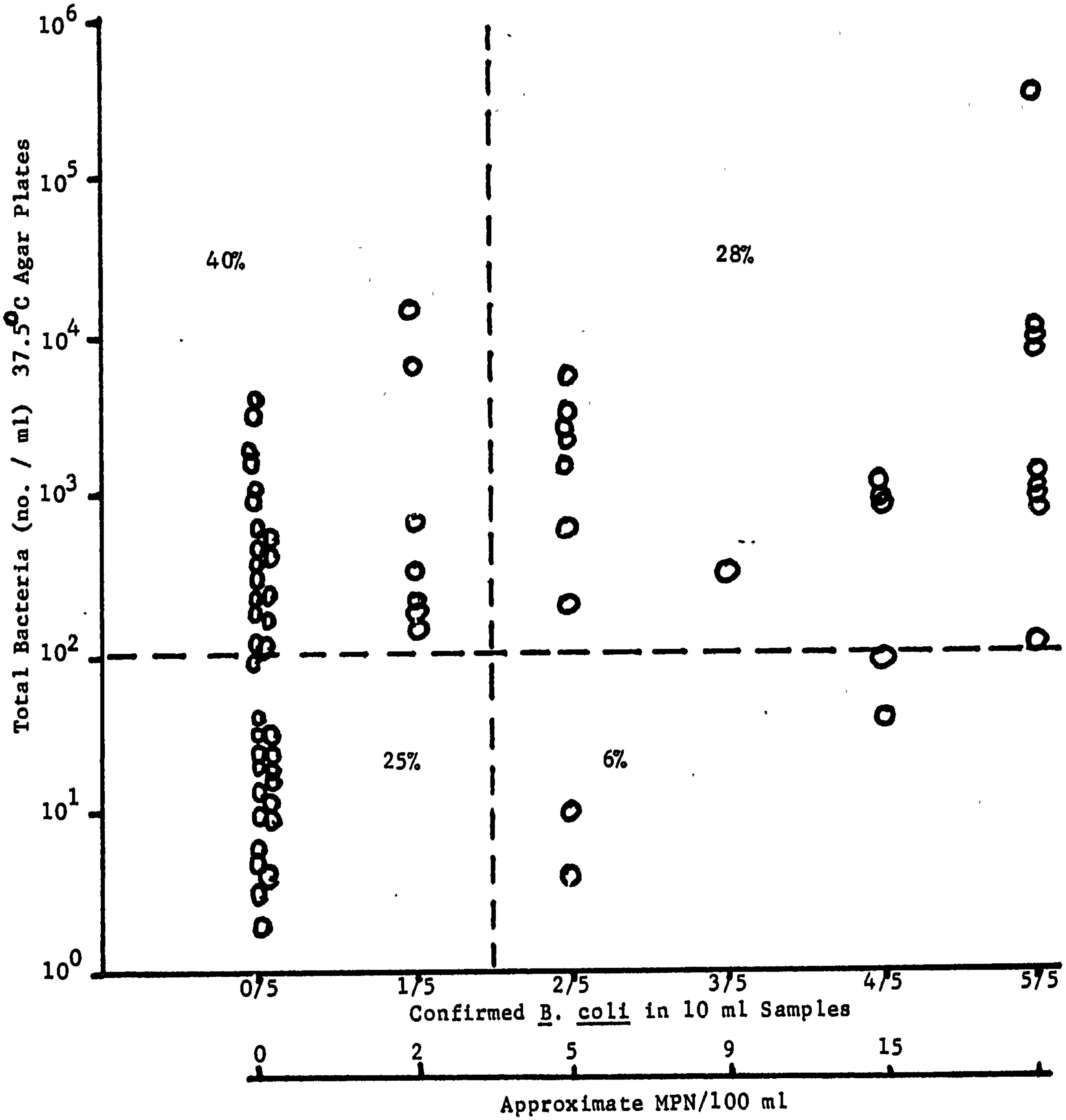
The USTD Standard specified units of permissible impurity for the 37°C agar plate count ($\leq$100/ml) and for B. coli ($\leq$2/100 ml) (USPHS, 1915). Using the procedures specified in Standard Methods (1912), analyses were to be done at least every six months (assuming that an analysis would be done before each certification (USPHS (1913)). The commission considered this "strict" standard to be attainable "without prohibitive expense" by simple treatment processes or source protection (Monfort, 1915). In addition, the commission stressed the importance of knowledge of "the source, treatment, and storage of the supply," but concluded that it is often "impracticable to obtain first hand authoritative information regarding the source and handling of the supplies" (Monfort, 1915). Consequently, the specified limits of impurity were established on the assumption that judgments would be based solely on bacteriological laboratory analyses. No physical or chemical limits were specified.

By 1915, 9000 of an expected 20,000 supplies had been tabulated and several supplies "of unquestioned purity" had failed certification (USPHS, 1915). A re-examination of Bartow's (1915) data reveals (See Figure II-1) that 75% of the samples exceeded one or both of the bacteriological standards.

Discussing the standard within weeks of its issue, Fuller (1915) prophetically observed that the Treasury Standard ". . . will unquestionably stir up a helpful agitation as to the reliability of bacteriological

Figure II-1

Bacteriological Quality of Drinking Water on Railroads (Bartow,1915)



methods." Professional discussion of the standard flourished for the next five years. The criticisms are many:

1. Water quality is variable and multifactor whereas the standard assumes constancy and employs only two factors (Wolman, 1919).
2. The standard is vague, thereby inviting abuse, about sampling frequency (Morse and Wolman, 1918; Hinman, 1920).
3. The assumed sampling frequency is inadequate (Hinman, 1920; Wolman, 1919).
4. Extreme or unusual conditions are of more importance than the average (Wolman, 1919; Hinman, 1920).
5. The methods are not adequately standardized and require individual judgment (i.e., the identification of typical colonies) (Morse and Wolman, 1918; Fuller, 1915).
6. The 5-tube B. coli test is not quantified and is of unknown precision (Morse and Wolman, 1918; Wolman, 1920).
7. Sanitary surveys provide more satisfactory evidence about fecal contamination (Hinman, 1920; Fuller, 1915; Rector, 1915; Frost, 1915).
8. Neither the plate count nor B. coli are of solely fecal origin (Prescott and Winslow, 1915; Fuller, 1915).
9. The B. coli test does not differentiate human vs. animal fecal sources or carrier vs. pathogen-free sources (Frost, 1915).

and 10. The standard is too strict, thereby penalizing many "safe sources" (Mason, 1916; Prescott and Winslow, 1915).

However, the superiority of Bacillus coli (alias colon bacillus) over plate counts in providing a numeric measure of the extent or degree of fecal contamination was not generally questioned (Wolman, 1920; Prescott and Winslow, 1915). But there was concern that supplies might be unfairly judged seriously contaminated. As Fuller (1915) pointed out, "[The colon bacillus] . . . represents, rather, a whole class or series of classes of bacteria resembling each other in a certain number of properties," some classes being saprophytes widely distributed in soils (Prescott and Winslow, 1915).

Given the near universal agreement on the necessity of the sanitary survey in judging sanitary quality (Whipple, 1908; Fuller, 1915; Mason, 1916; Winslow, 1915), the omission of such a requirement in the standard is notable. In part this was explained by Frost (1915). There are two approaches to controlling water supply on trains:

> First, by instituting an inspection of all sources of water supply and by maintaining careful supervision over them and over methods of handling, . . . [this method] necessitates the maintenance of a large force to keep up supervision over these sources [and their handling]. Or second by applying the same method used in the pure food laws, "that is, by requiring that the water . . . shall conform to certain specified standards of quality." The burden is put on the carriers.

So it would appear that given the ease with which the commission felt the standard could be attained, administrative expediency became a compelling argument in favor of strict laboratory standards over the sanitary survey. But at the state level, a poor sanitary survey was by far (92% vs. 48% for laboratory analyses) the most common basis for condemning a water supply (Whittaker, 1917 in Prescott et al., 1946).

As a rule for the measure of quality established by an accepted authority the Treasury standard in large part eliminated personal judgment in the interpretation of analytical results. Hinman (1920), Orchard (1918), and Wolman (1918) all attempted to distinguish between such regulatory standards and other possibilities. Hinman (1920) suggested three categories: 1) "Ideal Standards" or Water Quality

Goals (characteristics a highly pure natural water); 2) "Normals" or District Standards (commonly deserved characteristics of pure waters from similar sources in a restricted region or geological formation); and 3) Limit or Regulatory Standards (e.g., the Treasury Standard)—(maximum contamination level legally acceptable convenient for purposes of administration and enforcement). Wolman (1918) further stressed that although a standard of "good performance" includes concern with effluent quality, it should also consider performance consistency and plant control.

But it was Frost (1915) that first outlined the basic steps necessary to develop a rational standard. He laid out a cause/effect chain connecting fecal contamination with resulting illness. We will discuss in the next chapter subsequent attempts by Thomas and others to quantify this analysis.

Both Frost (1915) and Fuller (1915) discuss the impact of improved water supplies on the incidence of waterborne disease, suggesting other important factors: fly control, milk sanitation, food sanitation. The wholly judgmental basis of the Treasury Standard was obvious.

Whatever criticisms might have been levied against the Standard, it quickly became widely accepted even where no interstate carriers were involved. According to a survey of thirty-five state health departments reported by Hinman (1920, 1921), sixteen applied the Treasury Standard or one more strict. Similarly, 50 of 168 water treatment plants surveyed by Hinman (1920) used a standard at least as strict as the Treasury. Orchard (1918) proposed that the AWWA officially adopt the Treasury Standard since "the best results in any line of endeavor are secured only when a definite objective is in view."

But some remained concerned that "safe" supplies would be unfairly condemned on the basis of the Treasury Standard. Although it was generally accepted that water supplies showing 0.1 and 1.0 ml samples to be "regularly" positive for *B. coli* ( 20-40/100 ml) should be condemned (Mason, 1916; Prescott and Winslow, 1915; Orchard, 1918), interpretations of "frequent" positive reactions in 10 ml samples were more variable.

## Revisions and Expansions

In 1919, the Treasury Standard was amended to require a satisfactory sanitary survey report as a condition of certification (Hinman, 1920). But the first general revision began in May 1922 with the appointment of a commission ". . . to formulate definite specifications which may be used by the Public Health Service in administrative action. . . ." Although still only strictly applicable to supplies used by interstate carriers, the commission realized that the revision would serve as the standard for many public water supplies (Baylis, 1940). Chemical standards were added; limits on the total plate count were eliminated; the characteristics of the sanitary survey (i.e., source protection) were detailed; and the maximum permissible average *B. coli* level was reduced 50%, with an additional limit imposed on the 95 percentile. These revisions were promulgated in 1925. Subsequent revisions were issued by the USPHS in 1942, 1946, and 1962. In 1975, the USPHS Standards were superseded by the U.S. Environmental Protection Agency (USEPA) Primary Standards. These and various international standards are presented and compared in Appendix B of this report.

In establishing the 1925 PHS Standards, the committee chose to use ". . . the better class of municipal supplies as its standard of comparison with respect to safety . . ." (USPHS, 1925). This insured by experience both that risk of infection would be low and that the requirements would be achievable. By 1941, what was attainable went substantially beyond the 1925 Standards (Streeter, 1939; Baylis, 1940) and the American Public Health Association, the AWWA and the American Chemical Society called for a review (USPHS, 1943).

All these revisions were to some degree responsive to earlier criticisms, but many objections continued:

1. Methods continued to change, making comparisons difficult. Inhibitors were progressively dropped from coliform media (Gilcreas, 1952).
2. The bacteriological tests required twenty-four to forty-eight hours for preliminary results, reducing them to post mortem value (Gilcreas, 1952).
3. Objections that some coliform strains were resistant to chlorination, thereby making effluent standards difficult to attain were rejected by Levine et al. (1939). Based on study of 282 "chlorine resistant" strains, they were unable to find any strains that were intrinsically resistant. Instead they suggested that survival was due to protection from the disinfectant due to clumping.
4. Prescott et al. (1946), by implication, discussed limitations of the method. They were concerned: 1) with uniform recovery and specificity; 2) with reducing the judgments required of technicians; 3) with reducing the time, skill, labor and materials necessary; 4) with providing quantifiable results (MPN); and 5) with reducing the standard error of the MPN by increasing the number of dilutions examined.

Other standards were also proposed during this period. The British Ministry of Health (1934) chose not to specify either regulatory specifications (i.e., standards) or routine methods. Instead they described "the technical steps commonly used in sound practice . . ." to provide ". . . a reasonably complete picture of the bacterial content of the water. . . ." These steps included laboratory analyses and a sanitary survey. For unchlorinated piped supplies, they also outlined some "generally accepted deductions" for use in interpreting coli-aerogenes (alias Bacillus coli and coliform) levels, emphasizing that a change, regardless of level, is always suspicious:

| Interpretation | Presumptive coli-aerogenes/100 ml |
|---|---|
| highly satisfactory | 1 |
| satisfactory | 1 to 2 |
| suspicious | 3 to 10 |
| unsatisfactory | 10 |

Whereas many of the earlier critics were concerned that application of the Treasury Standard would unfairly fault many "safe" supplies, water-borne disease outbreaks in Minneapolis, Milwaukee, and several Ohio cities in the 1930's suggested that the standard was too lax. For both Minneapolis and Milwaukee, ". . . routine bacteriological examinations of the finished water . . . indicated satisfactory sanitary quality according to generally accepted standards" (Norcom et al., 1939). According to Norcom (1939), the Minneapolis outbreak (214 cases of typhoid fever) occurred in conjunction with high raw water coliform levels and low chlorine residual in the finished water. Although the Minneapolis Water Department found no contamination in the distribution system, the

Minnesota Department of Health found coliforms in about 6% of their samples with levels up to 10/100 ml. The Milwaukee outbreak (approximately 30,000 cases of gastroenteritis) occurred in conjunction with high raw water coliform and turbidity levels following a large rainstorm and snow melt. Cox (1939) concluded that the gastroenteritis was probably attributable to bacteria or an inorganic poison.

Responses were quite varied. Streeter (1939) saw no need for drastic revisions but suggested that the presumptive replace the confirmed count in standards. He was concerned that more stringent standards would unnecessarily reduce water availability and elevate plant capital and operation costs. Norcom and Wolman (Norcom et al., 1939) concluded that the source protection and plant design and operation were at fault. Wolman especially stressed that too much significance had become attached to effluent bacterial levels. McGrady (Norcom et al., 1939) promoted the utility of other tests (e.g., lactose fermenter, 20°C and 37°C plate counts, chlorine demand and residual).

In contrast, the Wisconsin State Board of Health (Streeter, 1939) and Baylis (1940) proposed substantially more stringent standards, including respectively a limit of about 0.2 and 0.1 MPN/100 ml for coliforms and a limit of 50 and 2/ml for 37°C plate counts. Both also specified chlorination requirements.

Later, Baylis (1940, and Derby, et al., 1960) expanded his proposals for revisions of the standard. These included 1) extending federal jurisdiction in setting standards; 2) enforcing these standards via design approval and plant inspection by state authorities; 3) implementing a system grading scheme that separately rated bacteriological quality, chemical quality, source and distribution system protection, personnel training, and emergency control procedures; 4) increasing sampling frequency; and 5) providing a graded scale of performance recognizing ultimate quality goals, minimum goals, acceptable levels, provisionally acceptable levels, and finally unacceptable quality.

These proposals reflected the definition of standards that had evolved by the mid-Twentieth Century. Wolman (1960) recognized five distinct objectives of standards:

1. Regularize measurement techniques,
2. Specify materials or processes,
3. Regularize administrative practice,
4. Regularize legislative fiat,
5. Regularize treatment plant performance.

The first two purposes were served by Standard Methods and the National Sanitation Foundation, but the remainder were considered to "not only justify standards" but to make them a necessity(Baylis,1940; Derby et al.,1946; and Zwick,1973).

But regulatory standards were often developed in advance of full scientific understanding (Wolman, 1960) and frequently, as cautioned by Hardy Cross (1952) became "frozen" at an immature stage and quite "recalcitrant to revision" (Wolman, 1960). It may be well to recall two comments by Sedgwick on standards (in Wolman, 1950):

> [Standards are] ". . . devices to save lazy minds the trouble of thinking."
>
> Standards are often the guess of one worker, easily siezed upon, quoted and requoted, until they assume the semblance of authority.

By mid-century, there were demands that standards be based on explicit rationale (Hopkins and Gullans in Derby et al., 1960) and that relative costs and benefits be balanced (Wolman, 1940; Davies, 1973; Kneese and Bower, 1968).

Earlier efforts to establish standards in large part reflected what was attainable by existing plants and personnel (PHS, 1925; Lee in Weston, et al., 1949). As such they were standards of good practice rather than the result of economic or epidemiological analysis. Because of the costs of meeting progressively more exacting standards, further revisions were subject to considerable public debate. A strong, defensible rationale had become a necessity.

## Overview: Achievements and Failures

As the cities of Europe and North America constructed community water supply systems during the last century, they all sought to provide "pure" water (Blake, 1956). But specifically what constituted purity or impurity or specifically how contaminated water might cause disease were unanswered questions. By 1880, the germ theory of disease was on firm bacteriological, medical, and epidemiological ground, and the sanitary survey provided some basis for defining purity. But just how important were improved water supplies in reducing the incidence of cholera, typhoid fever, and other water-borne diseases? Specifically, how important was improved water qulaity relative to the amount available or its accessibility or to other sanitary improvements?

That fecal contamination of water supplies could cause epidemics had been shown conclusively by Snow (1855) and others.* That improved water supplies reduced the incidence of typhoid fever and other diseases was widely maintained at the turn-of-the-century. Evidence favoring this hypothesis included 1) the observed declines in national typhoid fever morbidity and mortality rates (Rosen, 1958); 2) sudden observed drops in local typhoid mortality rates following a switch to a "better source," the elimination of fecal contamination of the source, or the introduction of filtration and/or disinfection (Mills, 1890; Fuller, 1915; Longley, 1915). Improvements often appeared to also reduce other diseases such as pneumonia and bronchitis, not generally considered to be water-borne (Sedgwick and McNutt, 1910). In 1904, Hazen proposed that, as a rule-of-thumb, for each typhoid fever death avoided by improving water supply, two or three deaths due to other diseases would also be avoided (Sedgwick and McNutt, 1910).

However, as White (1977) has recently and Frost (1915) and Fuller (1915) had earlier pointed out, "Trouble arises in trying to sort out water from other factors having an influence on health... ." Improvements in sewage disposal practices, milk sanitation, immunization programs, and in the control of flies and other insects influence typhoid fever rates (Frost, 1915; Fuller, 1915). Such complicating factors prevent the

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*Including Koch himself who mapped the distribution of cholera in Hamburg in 1892, much as Snow had done almost a half century earlier, and demonstrated the clear differences between water supplies (Mason, 1916).

clear identification of all but the grossest sources of exposure to typhoid. Even in those instances, interpretations may be less than clear-cut.

For example, Mills (Mason, 1916) attempted to show in 1890 that typhoid fever mortality rates generally decline when unprotected town wells were replaced by a community water supply. He compared 1859-1868 average typhoid fever mortality rates in sixteen Massachusetts towns depending on wells with the corresponding rates for 1878-1889 following the introduction of public supplies. Of the sixteen towns, 81% experienced reductions in rates averaging about 50% and ranging from about 20% to 65%. Although curiously not tabulated by Mason (1916), two towns experienced <u>increases</u> in rates of 24% and 33% and one town showed no change. What is seriously absent from this analysis is an analysis of comparable towns that did <u>not</u> change water supply, i.e., a control.

In contrast, the analysis of variations in typhoid fever rates in the Merrimac Valley did include controls. When a typhoid epidemic began in December 1890 in Lowell, Massachusetts, later moving down the Merrimac to Lawrence, an upstream town (Manchester, New Hampshire) escaped the epidemic even though all three towns depended on the Merrimac for water supply (Sedgwick, 1902). Sedgwick and MacNutt (1910) showed that the age structure, the male/female ratio, the ethnic composition, the fraction that were immigrants, and the occupational make-up of the three towns were quite similar during this period. They attempted to demonstrate the influence of water supply and water treatment on typhoid fever and other disease rates by contrasting Manchester to Lowell and Lawrence. Figures II-2 and II-3 are drawn from their tables. By comparing average rates for 1888-1892 (i.e., prior to improvements in the water supplies of Lowell and Lawrence) with average rates for 1894-1898 (Lawrence) or 1896-1900 (Lowell) (i.e., after improvements), using Manchester as a control (no change in treatment), Sedgwick and MacNutt (1910) argued that not only did typhoid fever rates decline by over 70% after improvements but rates of pneumonia, bronchitis, tuberculosis, and other diseases not considered to be water-borne also dropped. As Mills and Hazen had done earlier, Sedgwick and MacNutt (1910) concluded that either by increasing "vital resistance" or by actually reducing pathogen levels, water supply improvements produced reductions in more than just typhoid fever rates.

Although it is undoubtedly true that water supply improvements reduce the risk of infection by water-borne diseases, the selection of 1888-1892 as the pre-improvement period unfortunately distorts the differences between Manchester and the "epidemic" towns and between before and after, specifically including the years of the epidemics and excluding the preceding years. Inspection of the figures will also reveal that endemic typhoid rates were apparently in general decline from 1883 to 1905 and that the three towns experienced essentially equal typhoid rates during non-epidemic periods. This suggests that other factors were involved.

More recent efforts to quantify the health benefits of water supply and particularly water quality improvements have not been notably more successful although more sophisticated (IBRD,1976; Kawata,1978a,1978b). As Kawata(1978a) has argued, the provision of

Figure II-2

Typhoid Mortality Rates in Lawrence, Lowell, and Manchester (Sedgwick and MacNutt,1910)

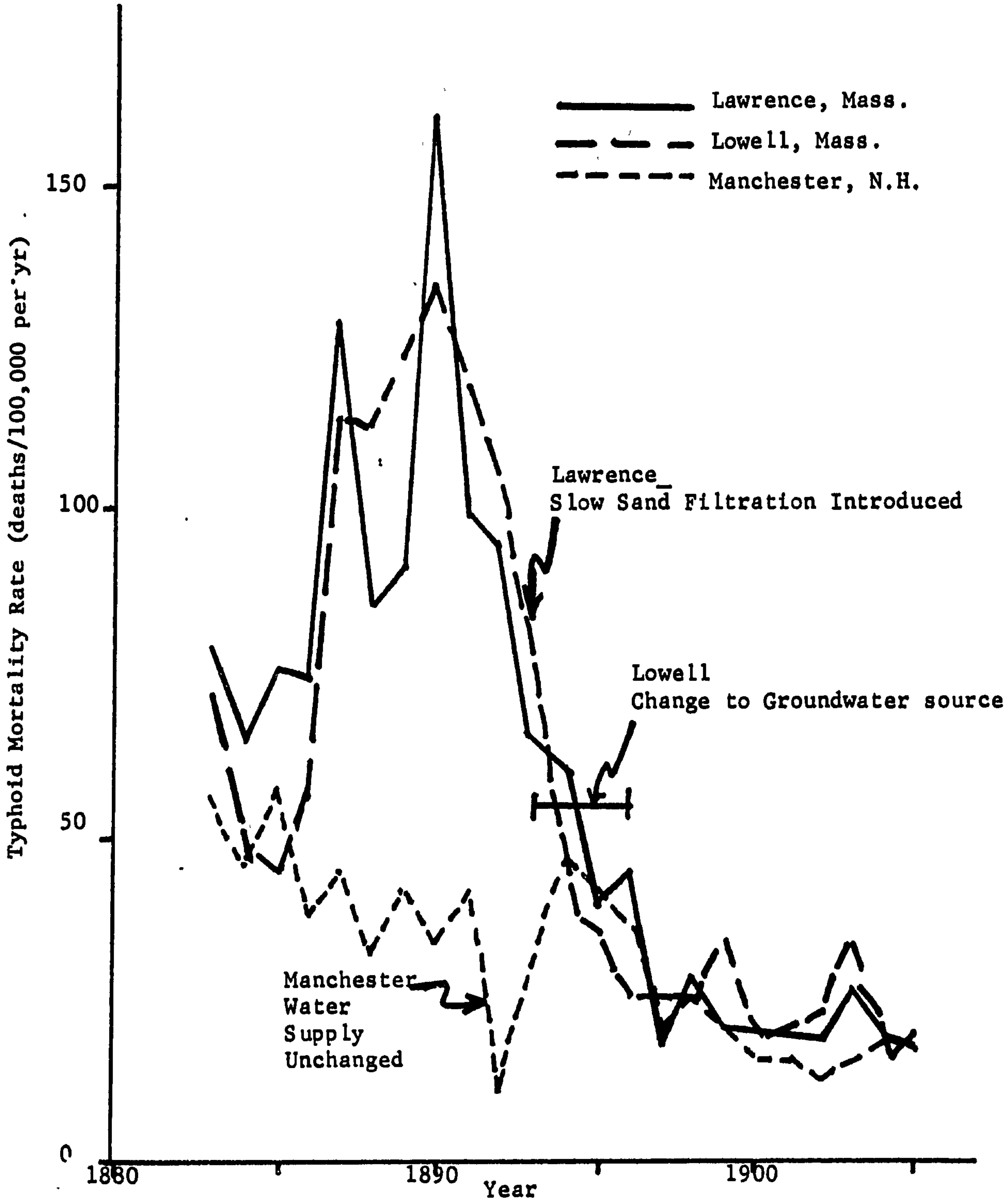
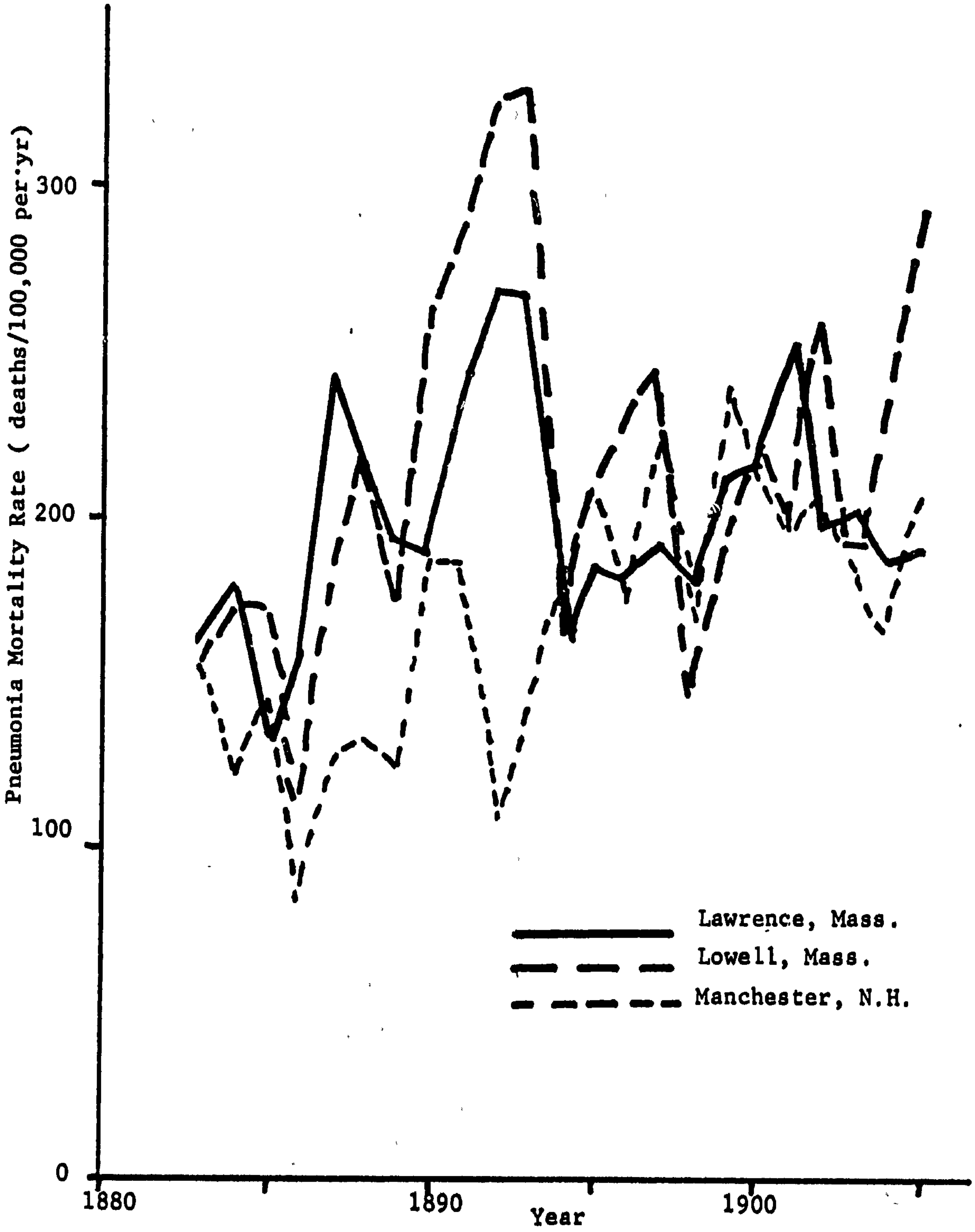


Figure II-3

Pneumonia Mortality Rates in Lawrence, Lowell, and Manchester (Sedgwick and MacNutt,1910)



uncontaminated drinking water will not result in health improvement if users continue to depend on contaminated sources because the improved supply is unpalatable, has frequent service interrptions, or requires long waits at public taps. Nor will water quality improvements alone produce health improvements if the principal anal-oral routes of exposure do not involve water-borne diseases per se, but rather fecal contamination of fingers or food.

Pride in the very real and substantial decline in urban deaths attributable to water supply combined with continuing concern about the causes of the remaining outbreaks motivated a series of "status reports" on typhoid and other water-borne disease: Johnson(1913), Wolman and Gorman(1931), Gorman and Wolman(1939), Eliassen and Cummings(1948), Weibel et al.(1964), Craun and McCabe(1973), and Craun et al.(1976). Most notably, typhoid mortality rates decline from $10/10^5$ persons/yr at the turn-of-the-century to $0.1/10^5$ persons/yr by mid-century.

But comparing 1920-1929 (Wolman and Gorman, 1931) with 1961-1970 (Craun and McCabe, 1973), it appears that some characteristics have not greatly changed. In both decades, 1) untreated ground water supplies, especially shallow wells, accounted for 25 to 50% of the outbreaks; 2) water supplies serving less than 5000 persons accounted for over 50% of the recorded outbreaks; 3) outbreaks in large supplies were most commonly the result of lapses in treatment or of distribution system deficiencies; and 4) some outbreaks resulted from consumers using polluted sources rather than use protected supplies because of taste/odor, excessive hardness, or mineral taste.

Moreover, urban-rural differences in the incidence of water-borne disease have long been observed. In 1916, Johnson (1916) estimated that for 1910-1913 rural typhoid mortality rates were over 10% higher than urban rates. Leach and Maxcy (1926) later observed that "rural" supplies experienced dramatically lower typhoid morbidity rates than systems serving 500 to 2500 persons. More recently, Taylor and Hutchinson (1975) and Whitsell (1975) investigated water quality in small water supply systems and in individual supplies in eastern states. Approximately 30% of the small public supplies had monthly average coliform levels (estimated from at least twelve samples) exceeding 1MPN/100ml and about 40% of the individual supplies had Membrane Filter total coliform levels in excess of 4/100 ml. Whitsell (1975) suggested that in most cases the contamination would have been avoided by proper site selection and construction methods. He specifically demonstrates the correlation of contamination with the absence of a well cover, of a substantial cement grout seal, of a water-tight casing, and of either drilled, driven, or jetted well construction.

## CONCLUSIONS

Judgments about the wholesomeness and palatability of drinking water have been made throughout history. Records and remains of other socieites suggest that opinions about quality were based on observed clarity, taste, and odor and on the kind of source,

Urban water supplies were initially constructed largely to provide an adequate volume for personal consumption and for fire protection.

The sanitary survey evolved from more general investigations. From about 1870 through 1913, the sanitary quality of supplies was evaluated predominantly on the basis of the survey. Laboratory analyses provided supplementary and corroborative evidence about contamination. For the conclusions to be meaningful, well-trained persons must conduct the survey.

Standards as a means for assuring the wholesomeness and palatability of drinking water evolved in a society experiencing multiple transformations: urbanization, industrialization, and centralization. Consequently, standards to some extent assume the institutions and objectives of urban, industrial, market society. Initially little more than professional guidelines for interpreting chemical analyses, standards increasingly became administrative tools with the promulgation of water quality regulations. They insured uniform, predictable requirements that were expedient for centralized administration of thousands of water supplies.

Almost all sanitary scientists and engineers through 1925 opposed widespread application of standards, fearing unfair indictment of supplies. Sanitary surveys were considered more reliable. But by 1950, many considered standards to be a necessity.

Because of the regulatory objectives, standards must be carefully formulated statistically to ensure the desired effect. Different statistical statements imply more or less severe requirements.

Urban typhoid mortality rates in the U.S. declined from about 49 deaths/$10^5$ persons/yr in 1880 to about 15 in 1913, to about 3 in 1930, and to less than 0.1 in 1977. Consequently, it is clear that substantial improvements were made prior to the application of regulatory standards and that the rate of improvement was not noticeably accelerated by the adoption of standards. However, some estimates of the effects of water quality improvements on disease rates are excessive. Improved excreta disposal practices, nutrition, milk sanitation, insect control, and other factors also contributed substantially to this remarkable decline.

# III. CONTEMPORARY PROFESSIONAL TOOLS

## INTRODUCTION

In the previous section we explored the historical development of techniques for assessing the wholesomeness and palatability of drinking water. In this section we will examine these further, but in a topical rather than an evolutionary context.

At the most elementary level, we judge a water by subjective impression: Does it taste and smell good? Is it clear? Supplies that fail this inspection may furnish a liquid necessary for life but they cannot be considered satisfactory.

With knowledge that waters contaminated by human feces probably contain pathogens, we may learn to recognize in the surroundings the possible routes of contamination and thus also to recognize the waters that are probably contaminated. Supplies that fail this inspection are either currently dangerous or are likely to be so in the future. It is tragic that such dangerous supplies continue to be used either because there are no more wholesome supplies available or because the danger is not perceived.

Even where the surroundings offer no suggestion of contamination, we may learn to identify special chemical, physical, and microbiological characteristics of contaminated waters that are detectable by laboratory analyses. The results provide clues about the nature and surroundings of the source. Unexpectedly high concentrations of essentially benign constituents may arouse suspicions of contamination, which in some cases, may be groundless. As with all clues, some are more convincing than others.

To simplify the interpretation of the clues provided by laboratory analyses especially where judicial or administrative action (or inaction) will result, limits of permissible impurity or regulatory standards are frequently specified. These standards not only direct judicial or administrative decisions but they also are applied in selecting a supply source in prescribing necessary source improvements and treatment processes, and in guiding the operation of the treatment plant and distribution system.

We will begin in this chapter by comparing the strengths and limitations of the sanitary survey and laboratory analyses in assessing the wholesomeness of a drinking water. Then we shall explore the rationale for several chemical standards and for coliform standards. We will conclude by discussing the types of interpretation errors possible and the inherent limitations of bacterial indicators of fecal contamination.

## LABORATORY ANALYSES AND THE SANITARY SURVEY

The continual attempts to develop a multi-variate index of water quality reflect the reality that no single factor provides a sufficient measure of quality. However, a few bacterial indicators have come to dominate all other laboratory analyses in the detection of fecal contamination. They are clearly more sensitive and generally more convincing and meaningful than are chemical indicators like chlorides, free and albuminoid ammonia, or oxygen demand. Chemical and physical analyses continue to directly reveal the presence of toxic materials like lead, arsenic, and fluoride and to indirectly measure aesthetic and utilitarian features like palatability and potential staining and/or laundering problems through tests for turbidity, color, taste and odor thresholds, iron and manganese levels, hardness, and others.

Many of these same concerns can also be addressed by field investigation or sanitary survey. Transformed from the broad studies by Chadwick and Shattuck of environmental factors influencing health to the more restricted examination of the surroundings and potential routes of contamination of water sources described by Fox and the Massachusetts State Board, the sanitary survey has come in the Twentieth Century to encompass the complete water supply system from raw water source through the distribution system and to entail an increasingly specific set of procedures.

Both the results of laboratory analyses and the observations from sanitary surveys require interpretation to be meaningful. Fox, Nichols, Mason, and Sedgwick all argued that this interpretation should be patterned after the medical diagnosis: conclusions should be consistent with both field observations and analytical results. This clearly may permit substantially different interpretations to be based on the same observations. To reduce the variation in opinion, others proposed constituent standards for the interpretation of laboratory results.

It is convenient to compare three classes of constituent standards: regulatory standards, normative standards, and goals.

Regulatory (or limit) standards include the familiar maximum contaminant levels specified in governmental regulations or legislation and "product" specifications contained in legal contracts. In both cases, the standards serve as uniform and impartial rules in judicial or administrative devisions and as explicit design criteria. Consequently it is desirable that such standards be stated unambiguously and not be easily circumvented.

Normative (or local or district) standards express expected concentration ranges for uncontaminated (or treated) waters of specific regions, from certain geological formations, (or after treatment). If "the state of change is a state of danger" (Whipple), then normative standards may effectively guide plant and distribution system operation. Since by their nature normative standards describe attainable levels, regulatory standards have sometimes been founded on normative standards (e.g., the performance of the "better class" of municipal treatment plants guided the formulation of the 1925 USPHS Standards).

If regulatory standards set a ceiling on the concentrations of various constituents, goals specify desirable levels. As goals, they need not be immediately attained.

In the next two sections of this chapter, the rationale for regulatory standards will be discussed and many limitations of the standards will be obvious. However several limitations are inherent in laboratory analyses <u>per se</u>: 1) Results for a sample may not be representative of the parent water body and 2) the estimated sample concentration may incorporate substantial measurement error.* Additional samples would reduce the first error. The second error might be reduced by application of membrane filter methods and by a change in dilutions examined. Comparable statistical issues are involved in specifying regulatory standards and are perceptively discussed by Thomas (1955).

Interpretation of the results of field investigations suffer to some degree from similar limitations. Certain intermittent sources of contamination may not be apparent at the time of the survey. Where pollution sources are present at a distance from the supply, their sanitary significance may be questionable. Several return visits and supplemental laboratory analyses may provide additional guidance.

Some questions of judgment in sanitary surveys may be at least partially resolved by field experiments. For example, studies by Kligler (1921), Stiles et al.(1927), Caldwell(1937a,1937b,1938a,1938b), Caldwell and Parr(1937,1938), and Butler et al.(1954) furnish a concrete basis for evaluating the impact of fecal sources near wells. In reviewing this issue, Salvato(1972), USPHS(1962), and Wagner and Lanoix (1959) suggest three general factors that influence the "safe distance": 1) the characteristics of the aquifer, e.g., the groundwater level, the hydraulic gradient during draw-down, particle size, and

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* For example, suppose the results of a conventional MPN coliform test (five tubes each of 10 ml, 1.0 ml, and 0.1 ml) show gas production in one of the five of the 10 ml tubes but in no others at that or other dilutions. The estimated concentration or MPN in that case would be 2/100 ml but in 5% of such test results the true concentration would be either less than 0.5/100 ml or greater than 7/100 ml.

mineralogy; 2) the discharge rate and the nature (chemical versus bacterial) of the pollution source; and 3) the well construction practices and the pumping rate.

The very nature of the clues provided by the sanitary survey lead to the implicit application of "good practice" standards for the selection and improvement of the raw water source, for treatment plant design and operation, and for other system components. Such standards focus on design, siting, and construction procedure and not constituent concentrations.

Unfortunately, we have been able to locate only one study explicitly comparing the effectiveness of laboratory and field techniques. Whittaker (in Prescott et al., 1946) summarizes experience using both methods in Minnesota. Laboratory analyses were solely responsible for condemning only 8% of all condemned supplies while sanitary surveys were solely responsible for 40%. The remainder (52%) were condemned on the basis of both. These results suggest that the survey imposes the more exacting requirement.

## SCIENTIFIC RATIONALE FOR CHEMICAL STANDARDS

In this section, we shall explore the scientific arguments supporting existing standards for arsenic, fluoride, nitrate, chloride, and iron. The concerns and approaches vary with each constituent, but some generalizations are possible.

Past professional experience, epidemiological studies, and plausible assumptions have all been used in formulating standards. Frequently, standards for toxic materials have been established below concentrations or daily intakes at which toxic effects have been reported. How much below remains a matter of judgment. Mechalas et al. (1972), on the other hand, have proposed that standards be based on explicit effect-concentration relationships and that the standard be specified to assure a limit on risk. In addition, Thomas (1963) has maintained that the availability of treatment technology, the costs associated with meeting candidate standards, the number of persons exposed, and alternative investments to promote public health should influence standard-setting.

For palatability and utilitarian or usability concerns, acceptance of consumers must be the central issue. This is obvicusly strongly dependent on local custom and opinion. Therefore, universal limits on turbidity, color, chlorides, and related factors have doubtful value; regional or national normative standards might be more reasonable.

## Arsenic

It has been maintained that the acute and chronic toxicity of arsenic to humans necessitates limiting its concentration in drinking water (USPHS, 1962; USEPA, 1975).

Surface waters in the United States contain a median arsenic concentration of less than 10 μg/l, with a range from less than 10 to 1,100 μg/l (Durum et al., 1971). Ground waters concentrations up to 85 mg/l have been observed (Kehoe et al., 1944a). In drinking water arsenic levels range from trace levels in most U.S. supplies to 0.1 mg/l (McCabe et al., 1970).

Arsenic occurs naturally in a variety of foods, and is artificially introduced in some via feeds or pesticides. Vegetables and grains contain an average of 0.44 mg/kg and meats average 0.5 mg/kg of arsenic (Schroeder et al., 1966). Shellfish usually contain the highest concentrations—up to 170 mg/kg (Monier-Williams, 1949). The daily arsenic intake in the United States is 0.137 - 0.330 mg (Duggan and Lipscomb, 1969).

Arsenic occurs in trivalent and pentavalent forms in both organic and inorganic compounds (EPA, 1975). The toxicity of the various arsenic compounds is extremely variable (Safe Drinking Water Committee, 1977).

The principal characteristics of acute arsenic poisoning are profound gastrointestinal damage and cardiac abnormalities (Safe Drinking Water Committee, 1977). The only symptoms of mild chronic poisoning, however, are fatigue and loss of energy. In more severe intoxication the following symptoms may be observed: gastrointestinal catarrh, kidney degeneration, tendency to edema, polyneuritis, liver cirrhosis, bone marrow injury and exfoliative dermatitis (DiPalma;1965).

A number of cases of illnesses resulting from the consumption of arsenic contaminated water have been reported. Well-water containing from 11.8 to 21.0 mg/l arsenic in Minnesota was associated with illness in thirteen people (Feinglass, 1973).

An unusual opportunity to study the effects of arsenic in drinking water arose in Antofagasta, Chile. Between 1958 and 1970, the city's water supply contained a flow-weighted average arsenic concentration of 598 μg/l, resulting in an incidence of cutaneous skin lesions (leukoderma, melanoderma, hyperkeratosis, squamous cell carcinoma) of 313/100,000 per year and in several deaths due to arsenicism. Children were found to be particularly susceptible. In 1971, the addition of a treatment plant reduced the arsenic level to 80 μg/l. Subsequently, the incidence of cutaneous lesions dropped to 19/100,000 per year (Zaldivar, 1974). In a follow-up study in 1977, it was found that children born since the installation of the treatment plant had not suffered cutaneous lesions but that children over six years old still had substantial arsenic residues in hair and nails (Borgono and Greiber, 1972).

The ingestion of roughly 3 mg of arsenic (probably as calcium arsenate) daily for two to three weeks, from contaminated soy sauce, resulted in numerous cases of facial edema, anorexia, and peripheral neuropathy (Mitzuta et al., 1956).

Exposure to inorganic arsenic compounds has been linked to cancer in humans by a number of studies. However, other known and unknown carcinogens may also have been involved (Safe Drinking Water Committee, 1977).

In a region of southwestern Taiwan, where artesian wells containing roughly 0.5 mg/l of arsenic had been in use for over forty-five years, a dose-response curve relating the incidence of blackfoot disease and duration of water intake was also noted (Tseng, 1976). The incidence of skin cancer in areas of England with an arsenic level of 12 mg/l in drinking water have been found to be unusually high (Neubauer, 1947).

In contrast, California well-water containing up to 1.4 mg/l arsenic did not result in any specific illnesses, although arsenic storage in hair increased when levels in the water exceeded 0.05 mg/l (Goldsmith et al., 1972). Consumption of drinking water in the United States containing 0.1 mg/l has not been reported to have any adverse health effects (USEPA, 1975).

With regard to the present interim USEPA Standard of 50µg/l, the Safe Drinking Water Committee (1977) noted that if the time factors for development of cancer are found to be reasonable, and given the detectable incidence of skin lesions in Antofagasta with an arsenic level of 80µg/l in the drinking water, the present USEPA standard may not provide an adequate margin of safety.

## Fluoride

Fluoride, an essential nutrient, is a normal constituent of all diets (National Research Council, 1968). At certain concentrations in drinking water it will prevent dental caries (Dean et al., 1941, 1942), but at higher levels, it can produce dental fluorosis, bone changes, and crippling skeletal fluorosis (USPHS, 1969; Hodge and Smith, 1954; Roholm, 1937).

In a survey of 969 community water supplies in the United States, fluoride concentrations ranged from less than 0.2 to 4.40 mg/l

(U.S. Dept. of Health, Education, and Welfare, 1969). Concentrations of fluoride in natural waters are largely dependent on the solubility of the fluoride-containing rocks in contact with the water.

Fluoride is present in nearly all foods. Fish, especially those eaten with the bones, fish-meal flour, and tea are particularly high in fluorides. In contrast, milk and most fruits are generally low in fluorides. The fluoride content of vegetables varies greatly (Safe Drinking Water Committee, 1977).

Estimates of the total dietary intake of fluorides have varied considerably (Safe Drinking Water Committee, 1977). Hodge and Smith (1970) estimated the dietary fluoride intake for areas with non-fluoridated water to be 0.3 - 0.8 mg/day; Kramer et al. (1974) estimated the intake to be 0.8 - 1.0 mg/day, including consumption of water-based beverages. Kramer et al. (1974) also estimated for the fluoridated cities an intake of 1.6 - 3/4 mg/day.

The prophylactic effects of fluorides vary strongly with concentration. Reduction in dental caries experienced at optimum fluoride concentrations may be reduced by as much as 50% when the fluoride concentration is 0.2 mg/l below the optimum (Chrietzberg and Lewis 1957, 1962). The fluoride levels recommended in the 1970 WHO European, 1971 WHO International, and 1975 USEPA standards vary inversely with annual average temperature since the amount of water ingested by children is primarily influenced by air temperature (Richards, 1967).

In the United States the only harmful effect observed from fluoride in water is dental fluorosis (Hodge and Smith, 1954; USPHS, 1969).

Water containing 8 - 20 mg/l fluoride that is ingested over a long period of time can result in bone changes (Hodge and Smith, 1954). Crippling skeletal fluorosis can occur when a total of 20 mg or more of fluoride is ingested daily for twenty years or more (Roholm, 1937). Effects of fluoride, in concentrations usually found in water supplies, are not very well documented.

Assuming a dietary intake of 1 mg/day, the margin of safety with fluoridated water has been estimated to be 2-8-fold for dental mottling, and 20-40-fold for skeletal fluorosis (Hodge, 1961). The Safe Drinking Water Committee (1977) considered the low margin of safety for mottling to be adequate given the years of experience with fluoridation without apparent objectionable mottling in healthy individuals. This is further supported by epidemiological studies in areas with naturally high fluoride levels (Hagan et al., 1954; Leone et al., 1954; AMA, 1957).

The margin of safety for renal patients and individuals suffering from polydipsia are lower than that for the average person. One known case and two suspected cases of skeletal fluorosis have been reported in areas of the southwestern United States with fluoride levels of 2-3.5 mg/l in the drinking water. They were attributed to a combination of renal impairment and very high water intake (Sauerbrunn et al., 1965; Juncos and Donadio, 1972).

A WHO report (1970a) indicates that to avoid objectionable dental mottling, fluoride should be removed when levels in water exceed 0.8-1.6 mg/l, depending on temperature. In an earlier study, Richards et al. (1967) concluded that 0.7-1.3 mg/l would be appropriate maximum levels, also depending on temperature. Ericsson and Ribelius (1971) in Sweden reported potentially objectionable mottling with fluoride levels of 1.2 mg/l. It is not clear whether this was due to high fish consumption (Safe Drinking Water Committee, 1977).

The interpretation of these results is complicated by the lack of consensus regarding the degree of mottling that is objectionable (Safe Drinking Water Committee, 1977). However, the current WHO and USEPA limits are based solely on the danger of fluorosis (WHO, 1970, 1971; USEPA, 1975).

## Nitrate

Many serious and occasionally fatal cases of methemoglobinemia in infants have been attributed to the consumption of well-water containing nitrate, and have prompted the adoption of nitrate limits in drinking water (WHO, 1958; USPHS, 1962; USEPA, 1975).

In a survey of community water supplies, nitrate concentrations ranged from 0.0 to 127 mg/l. Of those examined, 3% (nineteen systems) had nitrate levels above the recommended USEPA limit of 45 mg/l (10 mg/l as N) (Safe Drinking Water Committee, 1977). High nitrate concentrations are frequently observed in shallow wells in rural areas. Well-water in Missouri, Illinois, and Wisconsin frequently contain over 10 mg/l of nitrate-nitrogen (Larson and Henley, 1966; Dickey et al., 1972; Smith, 1970; Crabtree, 1970).

In general, human intake of nitrate is primarily from food rather than water. The mean food intake of nitrate plus nitrite in the United States is nearly 120 mg/day, mostly from vegetables such as celery, potatoes, melon, lettuce, cabbage, spinach, and root vegetables. These may contain up to several thousand ppm nitrate. Cured meat can also be an important source.

Acute toxicity of nitrate results from its reduction, under certain conditions, to nitrite in the stomach and saliva. The nitrite then oxidizes hemoglobin to methemoglobin. The latter cannot transfer oxygen to the tissues. Depending on the proportion of hemoglobin that is converted to methemoglobin, anoxia and death may ensue (Winton, et al., 1971; Safe Drinking Water Committee, 1977). Infants under three months old and particularly those with higher intestinal pH are especially susceptible to methemoglobinemia (Winton et al.,1971; EPA,1975)

Apart from the direct intake of water high in nitrates, the consumption of milk from cows or from mothers drinking such water may result in infant methemoglobinemia (USPHS, 1962).

The 1962 USPHS limit was largely based on a survey (Walton, 1951) of reported cases of nitrate poisoning in the United States. Walton found that no cases of poisoning were reported when the water contained below 45 mg/l of nitrate. In a later study, Sattelmacher (1962) found that 3% of 467 cases surveyed were associated with nitrate concentrations below 41 mg/l. Another retrospective study (Simon, et al., 1964) showed that 4.4% of 249 cases were associated with water containing less than 50 mg/l of nitrate.

These retrospective studies have been seriously criticized, however. The analytical methods used were prone to error and in many instances nitrate analyses were performed considerably after the case had occurred (USPHS, 1962; Safe Drinking Water Committee, 1977; Winton et al., 1971). Furthermore, boiling water prior to feeding may increase nitrate concentrations by as much as 40% (Winton et al., 1971; Safe Drinking Water Committee, 1977). Finally intake from other sources was not accounted for.

Recently, studies have related methemoglobin levels in the blood of infants to nitrate concentrations in water consumed. Winton et al. (1971) observed above normal methemoglobin levels in infants receiving a daily intake dose of 10-15.5 mg/kg body weight. Although there were no signs of methemoglobinemia, their methemoglobin levels fell to within the normal range when switched to low-nitrate water. Winton et al. (1971) estimated that where excessively boiled water and powder formula are used for infant feeds, water containing as little as 50 mg/l nitrate yields the 10-15 mg/kg daily dose. Similar results were obtained by Shuval and Gruener (1973).

However, many infants have drunk water containing over 45 mg/l nitrate without developing methemoglobinemia. Moreover, although many public water supplies in the United States routinely exceed this limit, only one case associated with a public water supply has been reported (USEPA, 1975; Safe Drinking Water Committee, 1977). It has been suggested that in these cases incidental protective factors may have been involved (Winton et al., 1971).

The 1962 USPHS and 1975 USEPA limits are solely based on the danger of infant methemoglobinemia. Both Winton et al. (1971) and the Safe Drinking Water Committee (1977) consider the present limit to be reasonable, given present evidence. The Safe Drinking Water Committee (1977) suggests however, that for some infants the present limit may not provide an adequate margin of safety. This disagreement at least partially reflects the confusing evidence available.

### Chloride

High concentrations of chloride in drinking water can produce an objectionable taste and may also enhance corrosion rates in the distribution system and in household appliances (Welsh and Thomas, 1960; McKee and Wolk, 1963; NAS-NAE Committee on Water Quality Criteria, 1972).

The median chloride concentration in the 100 largest U.S. water supplies was 13 mg/l, ranging from 0 to 540 mg/l (Durfor and Becker, 1964).

Concentrations of chlorides usually present in drinking water are not harmful to healthy humans (Negus, 1938; McKee and Wolf, 1963) but may be injurious to individuals suffering from heart or kidney diseases (Maxey, 1956; McKee and Wolf, 1963). For healthy individuals, levels as high as 4,000 mg/l are reported to have no effects (Maxey, 1956). However, concentrations above 4,000 mg/l may cause "gastric distress" (Sartwell, 1973).

Human tolerance to chlorides varies with climate and the amount of physical exertion. Chlorides lost through perspiration are replenished by those present in either food or drinking water (Welsh and Thomas, 1960; McKee and Wolf, 1963). In hot, dry areas salt is often added to the drinking water to help maintain chloride levels in the body (Welsh and Thomas, 1960). In the United States, especially in the Southwest, water supplies containing up to 600 mg/l of chlorides have been used without any apparent adverse effects (Negus, 1938; AWWA, 1950).

Thus, limits on chloride levels in drinking water have been principally based on aesthetic and economic considerations (WHO, 1961; USPHS, 1962; WHO, 1971). An early study on chloride taste thresholds was carried out by Whipple (1907), using a panel of approximately twenty persons. Richter and McLean (1939) recorded the taste threshold concentrations of sodium chloride for a panel of fifty-three adults. The effect of chloride in water on the flavour of brewed coffee has also been examined (Lockhart et al., 1955). The results of these studies are summarized in Tables III-1, III-2, and III-3. Whether the taste imparted by chlorides is objectionable or not is a matter of personal preference and habit (Whipple, 1907; McKee, 1963).

Few recommendations regarding acceptable chloride levels were found in the literature reviewed. Hibbard (1934) suggested a limit of 200 mg/l. The NAS-NAE Committee on Water Quality Criteria (1972) recommended a limit of 250 mg/l in public water supply sources, if sources below this level were available, assuming that chloride is not removed in the common treatment process (NAS-NAE Committee on Water Quality Criteria, 1972).

Table III-1.—Range of Chloride Concentrations Detected by Taste in Drinking Water by a Panel of 20 Individuals

| Salt | Chloride Concentration Detected—mg/l | |
|---|---|---|
| | Median | Range |
| KCl | 250 | 167-286 |
| NaCl | 182 | 121-274 |
| $CaCl_2$ | 160 | 96-224 |
| $MgCl_2$ | 372 | 149-560 |

Source: Whipple (1907) cited by USPHS (1962).

Table III-2.—Taste Threshold Concentrations of Panel of 53 Adults for NaCl

| | Chloride Concentrations—mg/l | | |
|---|---|---|---|
| | Mean | Median | Range |
| Difference from distilled water noted | 97 | 61 | 42-364 |
| Salt taste identified | 530 | 395 | 120-1,215 |

Source: Richter and MeLean (1939) cited by USPHS (1962).

Table III-3.—Taste Threshold Concentration of Chloride Ions in Water

| Salt | Threshold Chloride Concentration—mg/l |
|---|---|
| NaCl | 210 |
| KCl | 310 |
| $CaCl_2$ | 222 |

Source: Lockhar et al. cited by USPHS (1962).

## Iron

Iron, in domestic water supplies, can produce undesirable taste, staining of clothing and plumbing fixtures, and accumulation of deposits in the distribution system (McKee and Wolf, 1963; NAS-NAE Committee on Water Quality Criteria, 1972).

The average per capita dietary intake of iron is about 16 mg per day (Negus, 1938; Kehoe et al., 1944b; USPHS, 1962; McKee and Wolf, 1963).

Aesthetic and economic considerations have been the principle motives for limiting the amount of iron in drinking water (WHO, 1961; USPHS, 1962; WHO, 1970; WHO, 1971).

In a survey of 1,577 raw surface waters in the United States, the mean iron concentration found was 52µg/l with a range of 1-4,600µg/l (Kopp and Kroner, 1967). In ground waters, concentrations ranged from trace levels to 400 mg/l (Kehoe et al., 1944a). Levels in 380 finished waters in the United States averaged 68.9µg/l with a range of 2 to 1,920µg/l (Kopp and Kroner, 1967).

Cohen et al., (1960) studied the taste thresholds for iron of 15-20 people. Results of this study are presented in Table 4. Note that 5% of the panelists could not detect iron even at a concentration of 256 mg/l in distilled water. It appeared that some panelists were accustomed to drinking water containing substantial amounts of iron. Earlier reports specify a taste threshold of 0.1-0.2 mg/l for both ferrous and ferric ions (Balavoine, 1948; Kettering Lab, 1957). In contrast, Lockhart et al., (1955), using a panel of more than 18 persons, found 10 mg/l to be the taste threshold for ferric ion in distilled water.

With regard to staining and deposition, Hazen (1895) states that 0.3 mg/l of iron rarely causes any trouble, and that occasional precipitation may occur at 0.5 mg/l; concentrations of 1-3 mg/l, however, usually result in precipitation and render the water entirely unsuitable for laundering. Buswell (1928) and McKee and Wolf (1963) indicate that concentrations above 0.1-0.2 mg/l result in staining and accumulation of deposits. Problems of a similar nature begin to occur at approximately 0.3 mg/l according to both Hinman (1938) and Edwards (1947). Concentrations above 0.25 mg/l have been reported to produce turbidity and taste problems (Mohler, 1951). The maximum allowable limit suggested by Hazen (1895) and Hibbard (1934) is 0.5 mg/l. Connelly (1958) recommended a limit of 0.3 mg/l. The NAS-NAE Committee on Water Quality Criteria (1972) also recommended a limit of 0.3 mg/l for soluble iron in public water supple sources, under the assumption that treatment processes may not remove soluble iron. Limits as low as 0.1 mg/l have also been recommended (Klut, 1938; Schlirf, 1941).

Table III-4.—Taste Threshold Frequencies for Iron in Water

| Cumulative Threshold Distribution—% | Distilled Water | Spring Water |
|---|---|---|
| | Ferrous Ion Concentration—mg/l | |
| 5 | 0.04 | 0.12 |
| 50 | 3.4 | 1.8 |
| 95 | 256 | - |
| | Colloidal Ferric Oxide Concentration—mg/l | |
| 5 | 0.7 | - |
| 50 | 8.8 | - |

## SCIENTIFIC RATIONALE FOR COLIFORM STANDARDS

As noted in the historical analysis, Frost was the first to suggest that coliform concentrations in drinking water might be related by a chain of correlation and causation to the typhoid morbidity rate of the population served. The chain required estimates of:

1. the concentration of "intestinal bacteria" in the drinking water,
2. the ratio between human and animal contributions,
3. the ratio of _Salmonella typhi_ to coliform levels,
4. the volume consumed per person--day,

and 5. the dose-infection relationship.

In reverse order, this chain suggested a basis for establishing a standard explicitly relatable to morbidity rates.

Although Frost was unable to provide the necessary estimates to carry through the calculation, Thomas (in Weston et al., 1949) used an approach similar to Frost's to relate typhoid incidence to coliform concentrations. He used estimates of the _S. typhi_/coliform ratio and the dose-infection relation (1% single cell infectivity) made by Kehr and Butterfield (1943). Thomas assumed all coliforms originated in human feces. In a later application of the same approach, Thomas (1955) calculated that a coliform level of 1/100 ml in the drinking water of $2 \cdot 10^8$ persons would be associated with an average $2.2 \cdot 10^4$ cases of typhoid fever each year. Still later, Thomas (1963) developed a dose-infection relationship based on the disputable assumption that "Every pathoge ingested has the same likelihood of causing death . . .":

$$Q = e^{-KX} \qquad \text{III-1}$$

where $Q$ = probability of not becoming infected during year

$X$ = pathogen concentration in ingested water

$K$ = infectivity parameter, a measure of pathogen virulence

Thomas (1955) also demonstrated that under the same assumptions, the risk of infection is approximately linearly related to the average coliform concentration.

More recently, Mechalas et al., (1972) and Fuhs (1975) have proposed additional changes in Frost's approach. Mechalas et al. (1972) incorporate a log-normal probability function for the dose-infection relationship while Fuhs (1975) uses a derivative of equation III-1 above. Fuhs (1975) also considers the *S. typhi*/coliform ratio to be dependent not on the typhoid morbidity rate but on the fraction of the population that are "carriers," assuming a *S. typhi*/coliform ratio of 0.01 in their feces. Both, but particularly Mechalas et al., employ the results of clinical studies of the dose-infection relationship to estimate the necessary parameters of their models. Whereas Kehr and Butterfield (1943) had suggested that 1% of persons ingesting a single *S. typhi* bacterium would become infected, Fuhs (1975) estimated that from 1.5 to 6.7% and Mechalas et al. (1972) estimated that less than 0.01% would become infected.

None of these approaches addresses the dynamic characteristics of the relationship between morbidity rates and indicator concentrations in drinking water.—In contrast, Cvjetanovic et al.(1978) have developed and applied several dynamic epidemiological models (e.g., for typhoid, cholera, and other diseases) that incorporate the results of contemporary clinical and field studies. The models consider sub-clinical or asymptomatic infections, short- and long-term immunity, temporary and chronic carriers or excreters, incubation periods, and numerous other factors. However, the instantaneous morbidity rate is assumed to be proportional to:

1. The number of infectious persons in the population under analysis,
2. the number of susceptible persons involved,
3. the force of infection.

The force of infection depends on the ability of the pathogen to successfully colonize or infect the host and on the amount of exposure to the pathogen through fecally contaminated water, milk, food, or hands. Consequently, the force of infection mirrors excreta disposal methods, water supply characteristics, food handling practices, and other environmental factors. In applications by Cvjetanovic et al. (1978), the force of infection was freely adjusted to assess the qualitative effect of privy construction and other control measures.

The work by Thomas(1955,1960), Mechalas et al.(1972), and Fuhs(1975) at least in part models the force of infection as a function of coliform levels and other factors. Those and all such models of the force of infection must consider:

1. the ratio of the pathogen to the indicator level in sources of interest,
2. the dose of the pathogen encountered,
3. the dose-infection relationship.

For typhoid, the pathogen (Salmonella typhi) to indicator (coliforms) ratio in human excreta depends primarily on the number of carriers in the population. Roughly 7 to 20% of persons infected continue to excrete S. typhi for several months following recovery and 2 to 5% continue to excrete for possibly the rest of their lives (Cvjetanovic et al.,1978). However, these percentages conceal considerable variation with age and gender (Ames and Robbins,1943; Vogelsang and Boe,1948). Moreover, only about 10 to 30% of those becoming infected exhibit clearly diagnosable, symptomatic typhoid; unfortunately, persons infected sub-clinically may still become carriers (Cvjetanovic et al.,1978; Meselis et al., 1964). In addition, the rate at which carriers excrete the pathogen also declines following recovery (Mason,1916). This implies that the pathogen to indicator ratio reflects not only the current morbidity rate as Kehr and Butterfield(1943) proposed but also the rates throughout the preceding decades.

The second term, the dose encountered, depends on the available routes of exposure and on sanitary control measures. Frost(1915) and those following were predominantly interested in water supply mediated exposures. For that route, the dose encountered depends on the pathogen concentration (only indirectly on the coliform level) and on the volume ingested. However as Frost(1915) and Fuller(1915) pointed out, a substantial fraction of observed typhoid cases may be attributable to contaminated milk, food, shellfish, or hands or to contaminated water from unprotected sources. Although not the result of water supply contamination, these cases may still result in some carriers and thus modify the pathogen to indicator ratio.

Finally, the dose-infection relationship translates the exposure experienced to the consequent morbidity. Burnet and White(1972) review the effects of inheritance, age, and gender (i.e., host factors) on the relationship. They emphasize that these factors are often confounded with cultural patterns. Most of the information available on dose-infection relationships is drawn from clinical studies in which healthy, adult volunteers are exposed to selected pathogen doses. The work reviewed by Mechalas et al.(1972), Fuhs(1975), and Bryan(1974) unambiguously shows differences between pathogens and between persons and verifies that the mode of exposure is critical. For example, _Vibrio cholerae_ administered in buffered water produced infections at doses four orders of magnitude below the levels necessary without buffers.

Regrettably, the sampling errors inherent in testing small numbers of persons (particularly at low doses) and the undoubted differences in susceptibility between the volunteers and the overall population (especially with regard to age and general health) make it difficult to extrapolate from clinical studies to conditions of concern here -- large numbers of people exposed at very low doses. Fuhs(1975) and Mechalas et al.(1972) attempt to extrapolate by assuming that the underlying probability distribution is known -- Poisson and log-normal distributions respectively. Neither allowed for any fraction of the test populations to be immune. In other words, clinical studies designed to estimate the $ID_{25}$ (i.e., the dose necessary to infect 25% of those exposed) or the $ID_{50}$ are generally inadequate for estimating the $ID_1$ or the $ID_{0.1}$ .

To summarize, the relationships reviewed above or superior alternatives might provide an explicit basis for establishing a coliform (or other indicator) standard for drinking water based on typhoid (or other pathogen) control goals. However, any such analysis for typhoid or any specific pathogen would be of only limited applicability to other pathogens with distinct natural histories or to other regions or cultures with distinct patterns of exposure.

## UNCERTAINTY, RISK, AND SPECIFICITY

As stated above and as the preceding discussions verify, standards reflect past professional experience, epidemiological information, and plausible assumptions and they also reflect the availability and cost of water treatment methods and the number of people at risk. Because of these contradictory influences and because of inherent uncertainties, standards provide no absolute assurance of safety. For example, coliform levels below 1/100 ml do not always imply the absence of pathogens. Rather, low coliform levels suggest that it is unlikely that pathogens will be present at "dangerous" concentrations.

But this is not always the case as the Minneapolis and Milwaukee outbreaks in the 1930's and the Riverside, California outbreak more recently demonstrate. At Riverside, S. typhimurium levels were ten times greater than coliform levels. In these cases, the water was not considered contaminated when it was. This kind of error can obviously be reduced by making standards more exacting.

However as White (1977) has observed, stringent standards ". . . may lead to unnecessary condemnation of supplies that actually present little health risk." This echoes the response to the Treasury Standard by Prescott and Winslow (1915) and others. If for convenience we let $\beta$ represent the probability of making an error of this second kind (i.e., considering the supply to be contaminated when it was not) and $\alpha$ represent the probability of making the first kind of error, we may observe that reducing $\alpha$ frequently implies increasing $\beta$.

The magnitudes of $\alpha$ and $\beta$ are unknown, but Whittaker (in Prescott et al., 1946) compares laboratory analyses with sanitary surveys in terms of their respective $\alpha$'s: Of all water supplies condemned on the basis of the analyses and/or the survey, the survey and the analyses would have "passed" 8% and 40% respectively.

Although their magnitudes are unknown, both $\alpha$ and $\beta$ might be reduced by developing more unambiguous or specific tests for contamination. Ideally, such tests would be positive for all contaminated waters and negative for all others. This implies that the indicator is found dependably in all contamination sources and in no others, i.e., the indicator is absolutely specific to contamination sources.

However, alternatives to constituent standards as arbiters of wholesomeness and palatability do exist. First, the sanitary survey might be re-emphasized. Second, the dichotomous good/bad response implicit in regulatory standards might instead be graded after the fashion of the British Ministry of Health Standard (Hobbs, 1950). Both measures would re-introduce common sense and professional judgment back into interpretation of water quality. Finally, White et al. (1972) and White (1977) suggest "good practice" standards for a spectrum of possible supply improvements, beginning with individual protected supplies. Such standards might specify materials, construction methods, and operator training.

But with these alternatives too, analogous errors are still encountered and more specific tests or specifications might still reduce $\alpha$ and $\beta$.

Increased specificity has been a long-standing objective of sanitary science and engineering, from 20°C gelatin plate counts through tests for E. coli type I. Geldreich (1966) outlines the early development of bacterial indicators. Between 1900 and 1915, classification systems for "color bacillus" types were repeatedly formulated to identify the specifically fecal types. In 1938, Parr (in Geldreich, 1966) proposed a system recognizing sixteen types based on four tests: 1) Indole production from tryptophan, 2) acid production (indicated by methyl red), 3) acetylmethylcarbinol production (Voges-Proskauer test), and 4) the citrate permease test. The IMVC system (Indole, Methyl red, Voges-Proskauer, Citrate permease) is by far the most common coliform classification; three types were considered characteristics of feces and three characteristic of soil, with ten intermediates.

Parallel with these developments, the 20°C agar or gelatin plate count was replaced by the 37°C plate count as the most specific test. This in turn was superseded by the total coliform test, which in turn was replaced by the fecal coliform test. Most recently, several rapid(i.e., they can be completed in a few minutes to a few hours) tests for total bacteria and coliforms have been developed (Geldreich,1979). These include adaptations of the Limnulus endotoxin assay (Jorgensen et al.,1976) that effectively provide total counts of gram-negative bacteria, radioactive label release assays for substrate degredation, and immuno-fluorescence staining procedures that are strain-specific. For each of these conventional or rapid tests, two distinct questions must be addressed: to what extent are organisms from non-fecal sources included by each test and to what extent do fecal sources not contain organisms positive to each test. This again is equivalent to considering values for $\alpha$ and $\beta$.

Geldreich (1966) also summarized the results of extensive field work on the composition of coliform populations from different sources. Table III-5 compares fecal with unpolluted soil samples. Table III-6 compares the composition of "clean soil" coliforms with coliforms from human mammalian livestock, and avian feces; the genus (or genera) corresponding to the IMVC types are also given. Clearly, there are no wholly fecal or wholly soil coliform types. Elsewhere, Dufour and Cabelli (1975) have found that 50% of Klebsiella strains isolated from fecally uncontaminated industrial wastes are positive to the fecal coliform test. By contrast, the Safe Drinking Water Committee (1977) reports that about 5 to 10% of Escherichia isolates cannot ferment lactose. It thus seems unavoidable that misinterpretations will occur.

This is further complicated by variations in the coliform composition over time in the fecal flora of individuals. Zubrzycke and Spaulding (1962) and Holdeman et al. (1976) found that the coliforms made up a minor fraction of the fecal flora and exhibit considerable variation both between persons and over time. Geldreich (1966) summarizes time

Table III-5.—Comparison of Fecal and Soil Samples

| | Fecal* Samples | Unpolluted** Soil Samples |
|---|---|---|
| ++– – | 91.8% | 5.6% |
| Escherichia Group (++– –,<br>–+– –,<br>+– – –) | 93.3 | 8.9 |
| Fecal coliforms | 96.4 | 9.2 |
| I + | 94.0 | 19.4 |
| M + | 96.9 | 75.6 |
| V + | 5.1 | 40.7 |
| C + | 3.6 | 88.2 |

*8700 isolates
**2300 isolates

from Geldreich (1966)

Table III-6—Comparison of Coliform Populations from Soil and Fecal Sources

| Genus | IMVC Type | Human Feces | Mammalian Livestock Feces | Avian Feces | Unpolluted Sod |
|---|---|---|---|---|---|
| Escherichia | + + − − | 87% | 96% | 98% | 5.6% |
| Klebsiella | + + + + | 0.1 | 0 | 0 | 7 |
| Klebsiella | − + + + | 0.5 | 0 | 0 | 8 |
| Klebsiella or Enterobacter | − − + + | 5.4 | 0 | 0.1 | 19 |
| Citrobacter | − + − + | 1.1 | 0 | 0.3 | 48 |

from Geldreich (1966)

series studies of the coliform flora of three persons. Over the three-year study, the dominant coliform strain dramatically shifted in two persons. IMVC types characteristic of *Escherichia*, *Klebsiella* or *Enterobacter*, and two intermediate types were each dominant in at least one fecal sample.

Additionally, White et al. (1972) argue that many common tropical soil bacteria are positive for the total coliform test and to a lesser degree for the fecal coliform test. It may prove worthwhile to repeat Geldreich's work in different regions.

In summary, *Escherichia coli* type I is the most specific indicator of fecal contamination; the fecal coliform test is slightly less specific. Dufour and Cabelli (1975) and others have argued for the addition of urease and oxidase tests to further increase specificity. Total coliforms, the 37°C plate count, and the 20°C plate count are in turn decreasingly specific.

With the increasing specificity however, comes reduced sensitivity. As demonstrated above, the fecal flora of some individuals are dominated by *Klebsiella* IMVC types rather than the *Escherichia* group. In addition, persons commonly excrete fewer *Escherichic coli* type I organisms than either fecal coliforms, total coliforms, or 37°C agar plate total bacteria.

Therefore, increased specificity reduces $\beta$ but may increase $\alpha$ because of inherent limitations. It seems unlikely that errors of interpretation would be simultaneously reduced by the adoption of novel indicators.

## CONCLUSIONS

Judgments concerning the wholesomeness and palatability of drinking water are commonly based on field inspections or sanitary surveys to identify probable sources of contamination and/or on laboratory analyses of sample constituent levels. Interpretation by trained workers is necessary in both cases, being guided either by the results of controlled field studies and of case studies or by sets of constituent standards.

Constituent standards reflect past experience, plausible assumptions, epidemiological studies, the availability and cost of treatment methods, the number of persons at risk, and local tastes. Attempts to analytically relate constituent levels to health are often limited by inadequate description of the host-pathogen relationship or of the toxicological relationship and by the statistical uncertainty inherent in clinical or epidemiological studies. Standards established for constituents unrelated to health respect local tastes and economic conditions.

"Good practice" standards for design, siting, construction, and operation of water supplies provide an alternative to regulatory constituent standards but without the associated sampling problems.

There are uncertainties inherent in all bacterial indicators of fecal contamination. Indicators that are the most specific are often also the least sensitive.

# IV. PROBLEMS IN APPLYING DRINKING WATER STANDARDS

## INTRODUCTION

This section will review some of the problems commonly confronted when questions of water quality arise in water supply projects. We will argue that water quality standards serve an important purpose in addressing such questions by providing goals and design specifications. We will further argue that problems associated with the adoption and application of recognized quality standards are, for the most part, caused by an unwarranted fear of potential social and economic consequences and by a failure to understand what purposes standards serve and how they should be used. Perhaps the greatest problem with any standard is that its acceptance seems to be the cause for discarding common sense and judgment. Unfortunately standards cannot substitute for these two ingredients in the mix that makes up sound project design, operation, and public health control.

## STANDARDS—COVERAGE AND PAST EXPERIENCES

A review of the standards adopted by eighteen countries and of the recommended standards proposed by WHO reveals a rather remarkable uniformity. (See Appendix B) Although differences occur in maximum permissible concentrations on a number of the chemical, physical, and bacterial parameters, with but few exceptions these differences are not large. With respect to bacterial standards and bacterial quality, it is noteworthy that there is 100% agreement on use of coliform organisms and "most probable number" or membrane filter counts as indicators of contamination of public health significance. Of the considerable number of the developing countries that have in recent years adopted drinking water standards either tacitly or officially, most have used the WHO recommended standards as their guide.

In contrast a wide spectrum of practice exists in the use and application of the standards. Where water quality standards exist and particularly where an effort is being made to observe the standards, externally assisted projects should in general comply and support. But when facilities or processes are required which are unreasonably costly or when the quality of the water reflected in the standards creates serious doubts about the safety of the water relative to WHO or other recognized standards, strict compliance may not be possible.

While there appears to be general recognition that standards serve a useful purpose whether as goals or design specifications, people of differing disciplines have in the past frequently been critical of specific standards or of implications associated with the application of particular standards. A review of the standards and of the problems which motivated the criticisms reveals among other things that most of the trouble has occurred over bacterial standards. Chemical standards have appeared to draw criticism only from those unable to distinguish between standards for toxic substances and those for such qualities as corrosivity, hardness, and other characteristics having little to do with health.

Additional criticisms involve urban and rural application of standards. There seem to have been few challenges of the accepted standards (such as those proposed by WHO summarized in Appendix B) in application to large urban water systems. The number of problems increases as the size of the systems decreases. It can be said with reasonable certainty that the problems of applying drinking water standards are essentially the problems of rural water supply quality.

So far as can be determined, radiological standards have not been of concern in any of the developing nations.

None of the above conclusions should be construed to mean that there have been no problems associated with application of the chemical and bacterial standards to large urban systems.* However, such problems are usually more amenable to economic analysis and to technical solution because of the ability to deal with them individually and the greater resources available. Broad policies and approaches which can be applied on a mass basis for numerous small systems make the problem of applying standards more difficult. It more than ever stresses the importance of judgment and technical competence in the interpretation of field and laboratory data.

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*Present concerns of cities in the industrialized countries over chlorinated organics and trace substances are regarded as areas that may require further attention by urban water officials in the developing countries. For the present, and until established and reliable data become available, emphasis needs to be placed on standards associated with bacterial safety and related to established laboratory and epidemiological data.

## STANDARDS OF SAFETY, ACCEPTABILITY, AND RELIABILITY

As discussed earlier in this report, constituent standards for drinking water in part reflect three concerns: public health, palatability/acceptability, and usability. The first objective is addressed in the standards which specify limits on toxic chemicals and bacteria. The second objective is related to maximum concentration of substances to be allowed to avoid making the water unpalatable and/or unattractive for drinking, e.g., color, taste and odor, turbidity. The third objective relates to characteristics of the water which influence corrosion rates, encrustation of piping systems, staining of laundry and plumbing fixtures, and excessive use of soap and softeners.

Bacteria in the numbers normally encountered in drinking water do not usually affect taste, appearance, or usability but are of primary concern in assessing the safety of the water for drinking. Bacterial standards reflect only public health objectives in most national standards.

However, strict observance of health-motivated water quality standards does not assure safety. The application of water quality standards as regulatory tools requires laboratory analysis of samples to establish conformance. To the extent that the samples are representative, properly collected, and properly analyzed, it can be determined that the water represented by the sample either meets or fails to meet the standard. But as noted earlier, a sample collected from an unprotected source may meet the standard at the time of sampling although the quality may change immediately after the sample is collected. Hence the need for a well designed sampling program in enforcing regulatory standards.

Standards which relate to acceptability and usability, while normally having no direct impact on safety, may have important indirect effects. Waters which exceed limits in color, taste, odor, iron, manganese, sulphates, and chlorides may not cause ill effects if used for drinking. However, the unwillingness of people to drink the water because of one or more of these qualities may lead them to return to unsafe sources: those which are more palatable or attractive but which are much worse bacteriologically. Waters which exceed standards related to usability and are objectionable because of their corrosiveness to piping systems, or because of their hardness, are usually only evaluated from an economic standpoint. But, they may also have certain health importance. For example, if a nearby pond produces soft water, or one better suited to clothes washing, it may attract people away from the very hard, but safe supply not only for washing purposes but for drinking and bathing.

Economically, it is usually less expensive to make a water bacteriologically safe to drink than to meet some of the chemical and physical standards, especially those concerning toxic substances. Fortunately, in most areas the task is commonly one of taking the present sources and through construction and protection, making them capable of meeting the bacteriological standards, without chemically altering a water which the people already are accustomed to drinking. In other words, discreet use of the standards.will permit emphasis on the important standards and an intentional disregard or downgrading of those standards which are of no health significance. This is not an exercise which lawyers and administrators find attractive.

However, it is an approach which recognizes that where people are accustomed to drinking a particular water even if chemically it exceeds the limits set by the standards and where the levels are not toxic, the objective should be to render the water safe bacteriologically.

## THE COST OF MEETING STANDARDS

Would it not be better to employ less stringent standards and to use the savings to provide water to more people, to increase convenient access to the supply, or to expand the quantity available? The implication is that construction of supplies which produce water meeting the WHO or comparable standards will increase costs substantially over those for less refined systems. Unfortunately, those who raise the question seldom indicate whether they would use another standard (e.g., one which permits twice as many coliform organisms, or twice as much arsenic, or three times as much nitrate) or none at all.

Previous paragraphs have noted that compliance with bacterial standards is usually much easier and much less costly than meeting chemical and physical standards. Where all available sources of water nearby contain levels of toxic substances in excess of the standards, compliance will usually be costly, requiring extensive treatment or transportation. Fortunately, there are not too many areas of the world where such problems arise, although these do include portions of Argentina, Yemen, and Tanzania. In these areas, it will have to be treated on a case by case basis, taking into account alternative sources, epidemiological evidence, and other factors.

Meeting most bacteriological standards should usually require no greater investment than that necessary to make the water simply accessible and palatable. In a few instances, it may involve the additional capital, operation, and maintenance costs of chlorination, and in a few others, the costs of filtration and potentially reduced reliability.

Where groundwater is available, it is almost always the best source of supply for rural areas . In most countries, properly located, constructed(i.e., protected), and maintained wells which are deeper than 10 ft. and which take water from consolidated aquifers will provide water which, with few exceptions, will meet the strictest of bacterial standards without need for chlorination or further treatment. Where wells and springs can be protected and made tight, reliance can be placed on good maintenance to yield water of high bacteriological quality. Routine laboratory testing or further treatment will normally not be required and costs need be no greater than if no standards were to be met.

In rural areas where surface water is the only available source, some form of treatment will be necessary to meet safety standards. Treatment must include making the water acceptable for drinking by the people and should also include making it safe. The cost of doing both will usually be little more than for one. Depending on raw water characteristics, making a surface water suitable for drinking can range from simple settling to chemical precipitation and filtration for reduction of turbidity. It may sometimes also include taste and odor removal and reduction of iron and manganese. Each of these processes directly concerns acceptability of the water for drinking.

Some will affect usage. Where these capital and operation costs have been accepted and where the potential logistic problems have been satisfactorily solved, the cost of adding chlorination to any one of these steps required to make the water palatable involves such a small additional investment that it is usually insignificant (Saunders and Warford,1976; World Bank, 1976). The savings derived from foregoing this additional investment would not help a substantial number of people in other communities to improve their water supplies.

In some instances, raw water may be acceptable for drinking by the local people without further treatment because they have become accustomed to it. Certainly in these cases, the incremental cost of making the water conform to the bacterial standards can be substantial. For communities of limited size, simple infiltration systems can be installed requiring limited maintenance and having low operation costs. The cost of systems for larger communities, while not great, may lead some to argue that the funds would be better used for construction of facilities in an adjoining community. However, water-borne and water-washed bacterial and parasitic diseases usually are the predominant causes of morbidity and mortality among all ages in many developing countries (Saunders and Warford,1976). Consequently, any dramatic relaxation of standards relating to water-borne diseases may be difficult to justify, even though meeting the standards may occasionally delay the time when other supplies may be improved.

## CONCLUSIONS

Laboratory analyses and water quality standards for interpreting the results are useful but limited tools for the experienced technician in the design, operation, and public health control of water supply systems. It is critical, however, that the limitations be recognized. Not all standards spring from public health interests directly and thus require implementation in harmony with local tastes and customs. In addition, the sampling procedures and frequencies that are practicable in many developing nations seldom provide an adequate basis for assessing contamination, especially from intermittent sources.

Uniform application of water quality standards has often been criticized. Most objections have focused on applying standards to small, rural water supplies. It has been argued that the resources used to meet stringent standards might be more effectively used to increase the accessibility, the quantity, or the reliability of the water supply. But example calculations suggest that where groundwater is accessible, siting and construction practices are appropriate, and objectionable mineral deposits are not present, the savings would be limited. Where surface waters are to be used, the incremental cost of meeting bacteriological standards over the investment necessary to simply make the water supply palatable/acceptable is not considered to be substantial.

However, where chemically contaminated sources must be used, the costs of meeting the standards will undoubtedly be substantial, assuming treatment processes do exist. Where treatment processes have not been developed, are we to prohibit people from drinking. Clearly common sense dictates that these cases be addressed individually with particular emphasis on epidemiological information.

In cases where the costs of meeting standards are high, questions of alternative uses of the resources are unavoidable. But even in those cases, the questions frequently arise from the mis-application of standards rather than from standards per se. Common sense indicates that condemning a protected well on the basis of a single sample showing 10 coliforms/100 ml is inappropriate and that even where that level is consistently observed (i.e., assuming anadequate sampling program), prohibition might drive users to unprotected and clearly contaminated sources. Technical expertise is necessary to interpret laboratory analyses of field water samples.

To conclude, rigid adherence to standards alone as a basis for acceptance or rejection or as grounds for legal and/or political action will seldom lead to prudent decisions or be in the public interest.

# V. — WATER QUALITY STANDARDS AND RURAL WATER SUPPLY PROGRAM OBJECTIVES

## RURAL WATER SUPPLY OBJECTIVES

### Human Health

There can be little doubt that rural water supply programs in developing countries are intended in part to produce improvements in the health of the population served. The literature, the policy statements of government and of international organizations, and the conventional wisdom of the water supply profession all reinforce this view. Improvement in human health is regarded with essential unanimity as the major (in some cases, only) objective of rural water supply programs.

This choice of objective is consistent with the last seven or eight decades history of water supply improvements in urban areas of developing countries and in urban and rural areas of developed countries. Other objectives (e.g., increased convenience or economic development), where present, have tended to remain subordinate to the concern for human health.

In contrast, it seems likely that the eighteenth and nineteenth century development of water source works, storage, and distribution facilities for the great urban centers of the world was motivated mostly by a desire for continued economic development and protection of real estate investment(fire protection)(Blake,1956). The introduction of water treatment near the beginning of the twentieth century and the subsequent development and refinement of water quality standards, however, reflect nearly exclusive interest in the public health. Specific concerns have evolved from typhoid fever and cholera through other bacterial diseases, protozooan parasites, viral infections, toxic inorganic chemicals, to today's interest in chronic exposure to toxic organic chemicals. But the overall motivation has remained the same: to eliminate, as far as possible, public water supply as a contributor to human sickness, disease, and death.

In the case of rural areas in developing countries, especially those within tropical regions, the water-related health concerns are many. To repeat from Section III, Saunders and Warford (1976), following Bradley (1971) and White, Bradley and White (1972), have classified diseases associated with water supply and sanitation deficiencies into five groups: (1) waterborne diseases, (2) water-washed diseases, (3) water-based diseases, (4) water-related vectors, and (5) fecal disposal diseases. A water supply of inadequate quality or quantity is usually implicated in the transmission of diseases from the first four groups; fecal disposal diseases (group 5) are associated mainly with poor food sanitation practices, including the consumption of uncooked fish and shellfish.

For the first four groups, Saunders and Warford (1976) list thirty-two individual diseases as being of immediate concern. At any one location, the concern may be limited to one or two diseases or may extend to nearly all those listed, especially in tropical countries. Whatever the concern, the provision of a safe and adequate supply of water is an important tool in reducing the incidence of a broad spectrum of human disease.

In some cases, providing and insuring the use of safe water is all that is required to break the cycle of transmission; in others, an adequate quantity of water is necessary to support the improved sanitation practices which will arrest the spread of disease.

Attempts to improve human health may arise out of simple concern for the welfare of other human beings, but this need not be the only motivation. National governments, for example, may desire to improve public health in rural areas in order to gain political support. Reduction in the incidence of specific diseases may also be linked to expected gains in worker productivity, with attendant gains in the welfare of the nation as a whole. Gains in rural productivity may be seen as instrumental in achieving a desired redistribution of income. Finally, concern over rural-to-urban migration patterns, leading to worsening social and economic conditions in urban areas, may suggest attempts to improve living conditions in rural areas, including improvements in rural public health. Although the ultimate objectives may vary, these possibilities share the same proximate objective: improvement in human health.

## Other Objectives

Rural water supply improvements may be desired for reasons that are essentially unrelated to human health, however. These objectives depend upon properties of water supply projects other than the safety or adequacy of the water produced. Instead, they grow out of the economic stimulation provided by project implementation, the amenity value of the completed project, or the perceived importance of the project as differentiated from its actual significance.

Water supply improvements require, in varying degrees, the allocation of labor, materials, machinery, and supplies. These resources are required for the initial construction period and, to a lesser extent, throughout the period of operation. Some of the required resources may be available in the rural area to be served, others are available elsewhere in the country, still others must be imported. The use of unutilized or underutilized resources already available in the country, regardless of the means of financing, is likely to improve the well-being of the country as a whole. When financing arrangements include, in part, grants or subsidized loans from developed countries, further net improvements in the welfare of the receiving country can be expected. While these results are not guaranteed (they depend upon the actual benefits obtained from the project being more valuable to the country than the opportunity cost of the resources used), the possibility of such gains can be expected to be of interest to national governments.

Apart from purely economic gains, the provision of a convenient and protected source of water contributes to the quality of everyday life in rural communities. Substantial human effort is often required to collect water from traditional sources (see White, Bradley, and White, 1972). The availability of a borehole with a hand pump, or of a pressurized distribution system with standpipes, may greatly reduce the community's aggregate water collection effort, freeing time for other activities. Individual building connections provide further improvements of this kind, but at substantially greater cost. Among other results, increased convenience may lead to additional uses of water (e.g., household cleaning, garden irrigation, etc.) which, although not clearly related to public health, improve the life of the community nonetheless. At the village level, this is frequently a primary objective.

Apart from the objective improvements in health, economic conditions, and lifestyle which water supply improvements may bring is the question of perceived, or subjective, benefits. People living in the affected community, or in other areas, may perceive water supply improvements as beneficial in ways which go beyond actual results. For example, conspicuous investment in rural community infrastructure may be taken as symbolic of the central government's determination to improve the life of rural people and may contribute to reduced pressure for urban migration. Individual communities may take pride in the introduction of technology (boreholes, pumps, treatment facilities, etc.), regardless of any objective changes in health or lifestyle. Support for water supply improvements may originate in the expectation of these subjective results just as it may stem from a desire for more tangible changes.

## Conflicts Among Objectives

Improvements in rural water supply, therefore, may be undertaken for a variety of reasons. Multiple objectives appear especially likely for local, regional, or national governments or governmental agencies, where economic and political considerations are likely to compete with health concerns for the attention of decision-makers. Regardless of the number of individual objectives, it can be expected that improvement in human health will remain a major purpose of nationally or internationally funded rural water supply programs.

Even where health improvement is accepted as the sole objective, however, it may arise from any of several motivations. These motivations may have various implications for the choice of alternative projects. A simple desire to relieve human suffering dictates a broad approach to the widest possible range of diseases, including attempts to improve water quality, to provide larger conveniently available quantities, and to bring about improvements in all forms of personal hygiene. Where the primary motivation is to increase labor productivity, attention may be focused on a smaller number of diseases, those most likely to incapacitate working-age adults (malaria, schistosomiasis, etc.). Particular stress may be placed on protected sources, water handling practices, etc., without comparable efforts to increase available quantities or to improve hygiene. Conversely, interest in the political benefits of health improvement may result in programs which selectively address the specific diseases of greatest popular concern and visibility (e.g., diarrheal diseases may be of greater concern than malaria, which is sometimes regarded as inevitiable).

If such different emphases on desirable project characteristics are possible within the single health improvement objective, it is clear that the introduction of other objectives, even in a subsidiary role, can only bring about further variation in project criteria. Economic considerations may affect the choice of technology, biasing it in favor of maximum economic stimulation. Interest in improving the quality of rural life, or in creating the appearance of maximum improvement, may divert resources from the areas where most health benefits could be achieved.

Project evaluation, therefore, requires a clear and unambiguous statement of objective before competing projects can be usefully compared. Where improvement in human health is the sole objective, or a major component in a multi-part objective, the underlying motivation for desiring such improvement should be explicit. Health is a multi-dimensional concept, and improvements in some respects may not be considered as valuable as improvements in others.

If the role of water quality standards in achieving the objectives of water supply improvements is to be understood, this necessary delineation of the role of possible human health improvements in the formulation of objectives is not sufficient. Attention must also be given to the linkage which exists between water quality standards and achieved water quality, under rural conditions; and to the linkage between achieved water quality and human health. These issues are outlined in the following paragraphs.

## WATER QUALITY IMPROVEMENT

A primary concern in the design of rural water supply improvements is the quality of the water that will be produced. In most cases, the range of alternative designs is constrained by the need to achieve a specified standard of water quality, such as the applicable WHO standard. In discussing the relationship between project design, standards, and water quality, however, a distinction should be made between the water quality that will result if the supply system operates according to plan, and the water quality that may result in the event of operational failure.

In developed countries, and in most large urban areas, well developed support systems can be expected to exist which assure the availability of passably competent operation and maintenance staff as well as necessary materials, chemicals, supplies, and spare parts. Under such circumstances, the probability of prolonged failure of some or all components of a water supply system is quite low. Project design, then, tends to focus on the water quality associated with proper operation and adequate maintenance of facilities. Operation, maintenance, and repair characteristics are taken as given, and water quality is viewed as a function of source characteristics and supply technology alone.

In rural areas of developing countries, however, no part of the support system can be taken for granted. Trained personnel, supplies, materials, or replacement parts may be completely unavailable, available only at the time of project initiation, or available sporadically throughout the life of the project. In the absence of an adequate support system, one or more components of the water supply system may fail. In some cases (e.g., treatment facilities) the system may continue to supply water, but at lower quality than planned; in other cases (e.g., well pumps) the supply of water may stop entirely, forcing the community to return to traditional water sources. In either case, the water actually used by the population is of lower quality than that envisioned by the water supply plan.

The quality of water provided to rural areas of developing countries, then,depends jointly upon three factors:(1) the characteristics of the source; (2) the technology chosen for source protection, conveyance, storage, and treatment (where applicable); and (3) the operation, maintenance, and repair practices employed throughout the life of the supply system. Rational planning would suggest that special attention be given to possible tradeoffs among these factors, and between each factor and the level of water quality to be achieved. When combined with further information describing the relationship between water quality and human health, knowledge of these tradeoffs should permit the rural water supply program to be achieved most efficiently, i.e., at the greatest ratio of benefits to costs. Such a planning approach argues against the use of fixed quality standards, to be met in every case, proposing that water quality be viewed as a variable, to be adjusted in each instance so that the resources devoted to the entire water supply program may be allocated to produce the greatest aggregate benefit.

An examination of the characteristics of rural water supply systems reveals that available tradeoffs frequently fall short of the level of flexibility that might be desired by a planner. Tradeoffs among the factors themselves certainly do exist, and they are well known to design engineers. Where more than one source can be considered, each source can be associated with alternative development and delivery technologies, and each technology implies specific operation, maintenance, and repair requirements. Each set of operation, maintenance, and repair requirements, considered along with the associated technology, implies a number of possible failure modes, and each failure mode has predictable consequences for the quality of the water actually used by the community in the event of failure. The source/ technology combination chosen is the one which, considering these relationships, seems likely to provide the desired water quality at the least cost and with acceptable reliability. This is not a simple design problem, but it is more manageable than would result from allowing design water quality to be a variable.

Still, the more variables available to the planner, the greater benefit can be achieved with limited resources. So the nature of tradeoffs between each factor and resultant water quality needs to be explored. It will be found that useful tradeoffs seldom appear. There are cases, especially with larger surface water supplies, where alternate source/technology combinations may result in different levels of expected water quality, all within a potentially acceptable range, but these cases seem rare.More often, the nature of the system under study restricts the range of choice to one or a few alternatives, none of which are noticeably sensitive to changes in the level of water quality desired.

This result reflects the limited number of sources typically available to a given community, the "lumpy" nature of technology, and the "bundled" nature of the resulting water quality improvements. Technology is lumpy when the relationship between the inputs(investment) and the outputs(water quality) is not a smooth one: more advanced technologies are used or not. It is not usually reasonable to opt for partial use of a treatment process. Improvements are bundled when they appear as joint products: achieving one particular quality improvement necessarily involves the achievement of one or several others. When a community has only one or two or three possible withdrawal points for water supply (perhaps one or two surface water supply points and a groundwater option), the number of alternative technologies will be limited as well. For each source, a few choices must be made as to type of protection to be provided, conveyance means, storage means, and the type of treatment to be employed. Each such choice tends to be lumpy, in that one level of water quality may result from using filtration, and another from not using it; intermediate levels may not be conventionally available. Groundwater may have one set of characteristics, surface water another, and no alternative sets of characteristics can be obtained.

Further, when a source/technology choice is made, improvements may be obtained for a number of attributes of water quality. These individual attribute improvements are inseparable; they are bundled, and not available separately or in other combinations. Even though it may be desirable to trade one water quality attribute for another in a given community, this is only possible if appropriate source/technology alternatives are available: the alternatives cannot be structured to create the choice.

In summary, for each individual water supply improvement project the quality of water actually provided depends upon the choice of source, of technology, and the related requirement for operation, maintenance, and repair. While a linkage certainly exists between these choices and water quality, the lumpy nature of technology and the bundled nature of quality improvements suggest that useful tradeoffs between the source/technology choice and achieved water quality will not necessarily be available for individual projects. Such tradeoffs may appear for occasional specific projects, and they may exist for aggregates of individual projects at the national, or international programming level.

## HUMAN HEALTH IMPROVEMENT

Water supply improvements may affect human health in a number of ways, related to the characteristics of the water actually used and the characteristics of the supply system. Health improvements occur when (1) the water supplied is relatively free from pathogenic and toxic substances,(2)when it is sufficiently palatable and available to encourage and permit increased quantities of use, and (3) when the arrangements for conveyance and storage minimize the exposure of humans to water-related or water-based disease vectors. It can be seen that water quality improvements contribute directly to health improvement in only the first case; water quality (in the sense of palatability) may be an indirect contributor in the second case. In the third case water supply improvements bring about health improvements for reasons unrelated to water quality.

The linkage is further complicated by noting that the causative agents for some waterborne diseases are not limited to water transmission; as noted above, they may be spread by food and personal sanitation practices as w Providing pathogen-free water, then, will not necessarily eliminate all "waterborne" diseases. Also, it is noted that palatability is a factor in inducing increased use of water leading, hopefully, to better sanitation practices and to lower incidence of water-washed diseases. The standard of palatability in any given community is determined by local experience and beliefs, including memory of the taste, odor, color, etc., of water from traditional sources. Water with a distinct taste may be preferred, for example, to a "better" tasteless, odorless supply. Where the former is a contaminated traditional source, and the latter is provided by a newly constructed supply system, increased use of water and better sanitation practices may not occur.

For these and other reasons, the linkage between water quality improvements and resulting improvements in human health is a complex one, difficult to observe in practice, and more difficult to predict. Attempts at empirical measurement of the linkage have, understandably, encountered serious difficulty (Saunders and Warford, 1976, Appendix A). Reviewing the problems associated with twenty-eight specific studies, Saunders and Warford(1976) conclude that the studies "provide evidence to reinforce the intuitive belief that the incidence of certain water-washed, water-borne, water-based, and water-sanitation associated diseases are related to the quantity or quality of water . . . they give us little help, however, in determining exactly how much improvement in health can be expected from a specific water supply . . ." (Saunders and Warford, 1976, p. 42). There can be no doubt that the linkage exists; it is the ability to make specific predictions which is lacking, because the impact of water supplies depends not only on its quality and quantity but also on specific epidemiological conditions and social practices.

## CONCLUSIONS

Attempts to improve human health through water supply investment may reflect a simple concern for the welfare of other humans, a desire to gain political support, to improve worker productivity, to re-distribute income, or to halt rural-to-urban migration. Water supply improvements may be desired for reasons other than health improvement, including increased comfort and convenience, economic stimulation, and community pride. Project evaluation requires a clear statement of objective before competing projects can be usefully compared.

The overall quality of the water supplied depends on three factors: (1) the characteristics of the source; (2) the technology chosen for source development, protection, conveyance, storage, and treatment; and (3) the operation, maintenance, and repair practices employed. The design problem is to chose the source/technology combination which seems likely to provide the desired water quality at the least cost and with acceptable reliability. Water quality standards serve, at least potentially, to constrain this range of choice.

In many cases, design decisions may not be sensitive to changes in water quality standards, because of lumpy technology and bundled water quality improvements. Water quality standards, then, are only one of a number of factors which determine how the objectives of water supply improvement programs are achieved and are more or less important in specific cases. The direction and magnitude of water supply investment may be sensitive to quality standards, but not in every case. The true role of water quality standards can only be assessed in the context of actual water supply programs developed at the national or regional level.

Where water supply systems are designed to meet a uniform set of quality standards, changes in those standards may produce changes in the cost of an overall program and changes in the benefits achieved. This is not because tradeoffs necessarily exist for individual projects, but because the mix of projects which would be constructed may change. Changes in quality standards which encourage the use of a specific technology tend to promote the construction of water supply improvements in communities where that favored technology seems most appropriate; communities where it is deemed less appropriate will be less likely to be chosen for investment, since the standards may not be achievable.

Case-by-case consideration of communities falling into the latter category can minimize undesired ill effects of such a policy, but the potential for water quality standards to modify the direction of investment should be clear. Unfortunately, the means to determine the significance of this effect would not seem to flow from analysis of general or specific characteristics of individual technologies or projects; rather, it lies in the analysis of actual water supply improvement programs as developed for entire nations or regions. Only at this level can the true role of water quality standards in achieving program objectives be assessed.