Technology and Child Survival: The Example of Sanitary Engineering
Author(s): John Briscoe
Source: *Population and Development Review*, Vol. 10, Supplement: Child Survival: Strategies for Research (1984), pp. 237-253
Published by: Population Council
Stable URL: http://www.jstor.org/stable/2807963
Accessed: 31/05/2009 17:40

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=popcouncil.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

Population Council is collaborating with JSTOR to digitize, preserve and extend access to *Population and Development Review*.

http://www.jstor.org

Technology and Child Survival: The Example of Sanitary Engineering

John Briscoe

This paper focuses attention on conceptual models in a specific sector, namely, water supply and sanitation, that has played a fundamental role in reducing infant mortality in industrialized countries (McKeown, Brown, and Record, 1972), and from which a similar contribution is expected in underdeveloped countries. The analysis has two major objectives. First, it is intended to demonstrate how conceptual frameworks arise in response to specific challenges, how they are modified to meet different challenges, and how such modifications and revisions must continue to be made when facing relatively new challenges such as those posed in underdeveloped countries. Second, through discussion of specific examples, a general methodology is presented for determining priority research needs when there is uncertainty about the values of many relevant parameters. Although concerned with the field of sanitary science, the paper illustrates how the neglect of socioeconomic dimensions of a problem can greatly compromise the effectiveness of a health intervention.

Sanitary engineering in industrialized countries

The modern history of sanitary engineering begins with the Industrial Revolution and, in particular, with three facets of that revolution. First, urban settlements of unprecedented size and concentration were created in a short space of time. In London, for instance, the size of the land area supporting 10 persons per acre expanded from 43 square miles in 1837 to 75 square miles in 1858. Second, a central tenet of the Industrial Revolution was that practical material problems could be solved through the development and application of scientific principles. And third, the wave of unrest that swept Europe in the late 1840s and culminated in the revolutions of 1848 led to an increasing concern with the economic and social conditions of the working class.

The development of sanitary engineering, in direct response to the challenges arising from these three factors, arose out of a world view formed by both social and natural scientists. Engels (1845), Virchow (see Ackerknecht, 1953), Chadwick (1842), and other social reformers of the nineteenth century drew attention to the critical role of environmental conditions in mediating the relationship between social and economic factors, on the one hand, and morbidity and mortality, on the other. Through the development of the "germ theory" by Pasteur, Koch, and others and the imaginative collection and analysis of epidemiological data on cholera in London by Snow (1854), and on typhoid in the Elbe Valley by Koch (1894) the biological link between water, sanitation, and health was established. In short, the conceptual framework of sanitary engineering was originally holistic, taking account of the social and economic antecedents of environmental conditions, of the engineering problems of facilities' design, and of the biological mechanisms linking exposure to disease.

Guided by this conceptual framework, sanitary engineers first tackled the development and testing of technologies to reduce the number of bacteria in drinking water. While sand filters had been used for centuries to improve the aesthetic quality of drinking water, the role of filtration in improving bacteriological quality had never been recognized. A number of experiments demonstrated that the number of bacteria in drinking water could be reduced by one or two orders of magnitude through slow-sand filtration.

A particular problem not solved by slow-sand filtration was the treatment of highly turbid waters. Building on the chemical-coagulation process (patented in 1884), the Louisville, Kentucky, Experiment Station demonstrated that so-called mechnical filters, preceded by coagulation and sedimentation, could solve the problems posed by these waters.

By the early twentieth century engineers were confident that good quality water could be produced by pretreatment followed by filtration. The most significant advances in water treatment, however, came with the introduction of chlorination in 1908. Not only was calcium hypochlorite a cheap and widely available chemical, but chlorination consistently eliminated pathogenic bacteria in drinking water.

Accompanying these scientific advances were simple but convincing demonstrations that use of these technologies resulted in the anticipated effects on public health. For example, a study in the Ohio River Valley recorded typhoid death rates per 100,000 of 76.8 and 74.5 in 1906 and 1914 respectively in 11 cities with untreated water supplies. By contrast, typhoid death rates dropped from 90.5 in 1906 to 15.3 in 1914 in 16 cities with untreated water supplies in the former year and treatment in the latter year (Maxcy, 1941). The Mills–Reinke Theorem, postúlated in 1910, held that, for every death from waterborne typhoid, there were several deaths from other diseases for which the causative agents were transmitted by water (Sedgewick and MacNutt, 1910).

The founders of sanitary engineering realized that the benefits of these advances could be enjoyed by everyone only if appropriate design rules and standards were developed for the guidance of engineers. In commenting on water quality standards in 1914, Alan Hazen reflected the comprehensive grasp that these pioneers had of the economic, engineering, and epidemiological factors that must underlie such design criteria:

> There is no final reason for such standards. They have been adopted by consent because they represent a purification that is reasonably satisfactory and that can be reached at a cost which is not burdensome to those who have to pay for it. . . . There is no evidence that the germs so left in water are in any way injurious.

This early period of modern sanitary engineering was thus one of dramatic advances. Indeed, by the early part of the twentieth century the scientific bases of all of the processes of conventional modern water treatment—coagulation, sedimentation, filtration, and disinfection—were understood, and technologies were developed for the practical application of these principles.

This success meant that the initial conceptual framework rapidly became outdated. It was modified in two fundamental ways. First, the study of the relationship between water and infectious diseases was no longer of much practical interest to design engineers, and, second, the achievement of anything but the complete elimination of bacteria from water became unsatisfactory. From its original broad conceptual framework sanitary engineering was thus rapidly reduced to the narrow technical dimensions characteristic of the "mature" profession. However, since the sanitary revolution was as much a social as a scientific revolution, this task was not simply a technical one, but was simultaneously an economic one, for water treatment had not only to be effective, but also to be sufficiently inexpensive so that high quality water could be supplied to and paid for by all urban residents in industrialized countries.

The effective and inexpensive preparation of water for disinfection has been the single most important water treatment challenge facing the mature sanitary engineering profession. Indeed, any textbook on water treatment is predominantly a book on water clarification; the bulk of the capital and operating expenses of a water treatment plant are those connected with clarification; and for a water treatment plant operator "good" water is equivalent to "low turbidity" water.

Simultaneously, developments were proceeding on the treatment of sewage. In the present context it is unnecessary to trace the history of this enterprise in similar detail. Suffice it to note that, as the conceptual framework of water treatment engineers was narrowed to concern with preparing water for disinfection, so the conceptual framework of sewage engineers was narrowed to the dominant concern of reduction of the Biochemical Oxygen Demand (BOD) of treated wastewater.

The "mature" conceptual model of the sanitary engineering profession thus represents a drastic simplification of the holistic perspective that characterized the original conceptual model. With this loss of holistic perspective, the discipline has undergone a process akin to the "involution" described by anthropologists in which human cultures, after developing a pattern for responding to an initial challenge, meet all new challenges by ever-increasing internal sophistication and differentiation rather than by developing creative new systemic responses (Geertz, 1966). In sanitary engineering the pre-World War I period was one of creative response and rapid fundamental progress, but in the subsequent 70 years there have been, in the words of the National Academy of Sciences (1977), "many refinements in engineering techniques but no basic changes in concepts of water and wastewater purification."

The objective of the application of scientific principles to any frequently encountered problem is the development of a set of simple "rules" that may be applied easily by someone with only a rudimentary understanding of the process by which the rules were developed. The degree to which such an objective has been achieved is a measure of the "maturity" of that particular application of scientific principles. Familiar examples in medicine would be the use of oral rehydration therapy for the treatment of diarrhea, or the use of penicillin for the treatment of pneumonia. In environmental engineering, such "maturity" was reached in the early part of this century with the development of simple design rules for deciding on the quality of water to be supplied and the price to be charged for it.

In the following paragraphs we outline what these water supply "design rules" are, how they were developed, and how their validity is dependent on the specific behavioral and epidemiological conditions prevailing in the industrialized countries.

In the design of a water supply system, the quantity, or "design flow," required by a population is simply determined by multiplying the population to be served by an "average per capita requirement" (in liters per capita per day) and multiplying this figure, in turn, by a factor that accounts for the fact that peak flows (which the system has to be able to provide) exceed the average quantity of water required. Once the capacity of the system is specified, the engineer is free to devote his attention to the detailed hydrologic and hydraulic design of the reservoirs, pipelines, and other components of the water supply system.

The second major system decision, the price to be charged for water, plays no part in determining the capacity. This is because the demand for water for domestic purposes in industrialized countries changes little as the price of water changes—in the economist's jargon, the demand for water is inelastic with respect to price (Howe and Linaweaver, 1967). Given this fact and the fact that utilities typically face no competition in providing water in a certain area, utilities could make enormous profits by setting prices very high. For this reason the prices that utilities can charge are usually regulated.

Finally, it should be noted that although public water supplies are considered a cornerstone to the maintenance of public health, consumers demand levels of service that far exceed those required for public health purposes, and thus the engineer and economist can make their decisions on capacity and price without concerning themselves with the epidemiological consequences of their decisions.

To the water supply engineer in an industrialized country these ''golden rules'' specifying the quantity of water to be supplied and the price to be charged for the water are entirely satisfactory. They have served the profession well for many years, and the engineer correctly feels little need or desire to explore their behavioral, epidemiological, or economic underpinnings. Indeed, paradoxically, the ''maturity'' of the science of water supply may be measured by the degree to which practitioners can remain ignorant of these underpinnings and yet continue to design (more or less) satisfactory systems.

Sanitary engineering in underdeveloped countries

What of the sanitary engineering response to the challenge of reducing water-related diseases through the provision of improved water supplies and sanitation facilities in underdeveloped countries?

First, consider the outlook inculcated during the training of the sanitary engineers who practice in these countries. Many of them are expatriates, recommending, where they are conscientious, ''exactly what I would recommend for my own home city (in North America or Europe).'' Where there are local sanitary engineers, they have virtually all been trained either in industrialized countries, or by teachers trained in industrialized countries. The textbooks used are those written for industrialized countries, the curricula are similar, and thus the conceptual framework drawn on in addressing the problems of underdeveloped countries is that of the ''mature'' sanitary engineering profession in industrialized countries.

Second, consider the challenge faced by sanitary engineers in underdeveloped countries. From a bacteriological point of view this challenge is different from that in an industrialized country not only because of the much lower proportion of the population served by adequate facilities, but also because a typical person in an underdeveloped country excretes many orders of magnitude more pathogenic organisms than a person in an industrialized country (Feachem et al., 1981). Economically, too, the situation is different. While paying off the capital cost of a multiple-tap piped water supply (typically about $700 per household) and a waterborne sewerage system (about $1200 per household) may not impose an intolerable burden in an industrialized country, the ability to pay is drastically different in an underdeveloped country, where annual household income often is less than $500. Finally, the demographic situation is different, since the underdeveloped world is still predominantly rural, while most people in industrialized countries live in towns and cities.

A hint of the inadequacy of the conventional sanitary engineering response to this challenge is evident in the fact that in the rural United States, where people are often poor by national standards but wealthy in international terms, many households—200,000 in North Carolina alone—have inadequate water supply and sanitation facilities, and outbreaks of waterborne diseases are not uncommon (National Demonstration Water Project, 1978; Craun and McCabe, 1973). In the underdeveloped countries conditions are a great deal worse, with water-related diseases endemic. WHO estimates that 23 percent of urban and 78 percent of rural inhabitants in the Third World do not have access to water supplies of adequate quality within easy walking distance, while far fewer have access to adequate sanitation facilities (McJunkin, 1983).

The anomalies arising from the application of the "mature" conceptual framework to this set of problems are numerous and can be illustrated by the following example. In Kenya, just 2 percent of the population are served by waterborne sewers (Mara, 1976). The majority of the wastewater treatment units are either trickling filter or activated sludge plants, that is, plants using a technology designed for use in industrialized countries. Few of these plants operate effectively. These simple facts notwithstanding, an enormous effort has gone into the drawing up of entirely unrealistic "master plans" for providing waterborne sewers and wastewater treatment plants to serve every urban inhabitant in Kenya.

It is thus no exaggeration to describe this situation as a crisis, since the contrast is so great between the magnitude and characteristics of the problem, on the one hand, and the conceptual models and tools available to address the problem, on the other hand.

The history of science shows that in impasses of this sort it is often from outsiders, and usually outsiders not deeply schooled in the techniques and ideologies of the "relevant" profession, that fundamentally new approaches may be expected.[1] It was thus surprising to engineers (but not to historians) that it was a biomedical scientist and not a sanitary engineer who stood back from the accepted "mature" sanitary engineering conceptual framework and asked, afresh, about the relationship between sanitary engineering and health in a rural Third World setting. As with many revelations of this sort, David J. Bradley's classification scheme, published first in 1968 (with Emurwon), at first appeared to simply systematize what was already widely known. In fact, however, Bradley's scheme for classifying water-related diseases raised questions that were quite different from those considered by the sanitary engineers who design water supply schemes in underdeveloped countries. In particular the classification scheme brought to the fore questions of behavior ("How does the quantity of water used vary as distance to the source increases?"; "How can people be induced to change the habit of bathing in schistosomiasis-infected streams?"); questions of economics ("What is the cost of achieving supplies of a given quality and quantity?"); and questions of epidemiology ("What are the effects of improving drinking water quality?"; "What are the health effects of increasing the quantity of water used for domestic purposes?"). While questions of technology ("What are appropriate supply and treatment technologies under Third World conditions?'') were by no means dismissed as unimportant, the classification scheme showed that the ''new sanitary engineering'' had to draw on four conceptual bases—behavioral sciences, economics, epidemiology and technology—rather than on the one—technology—on which the ''mature'' profession of sanitary engineering had come to rely.

Bradley's scheme has become familiar to most engineers working in underdeveloped countries and has already had an impact on the design of water supply schemes in these countries. As this paper will show, however, it still remains unclear exactly how to translate the concepts embodied in the classification system into practical design rules.

The conventional design procedure in underdeveloped countries

As indicated earlier, in industrialized countries it is possible to consider the fundamental engineering decision (viz., the capacity of the system) and the fundamental economic decision (viz., the price to be charged for the water) independently, and it is possible to ignore health considerations. In underdeveloped countries the situation is different.

First, because of the economic realities of these countries, the level of service, which is not a decision variable in industrialized countries, becomes a critical decision variable. In particular, the distance between the home and the point to which water is delivered both determines the monetary cost (and thus the price) of the supply, and affects, over a certain range at least, the quantity of water that will be used. Furthermore, the quantities of water used are such that there are generally increased health benefits to be reaped if increased quantities of water are used for domestic purposes. It is thus evident that in underdeveloped countries the engineering and economic decisions relating to water supplies and the health aspects have to be considered jointly. For instance, the price levied for water will affect the demand for water (and thus the capacity that the engineer should design for) as well as the health of the people because price will affect both choice of source (and thus choice of water quality) and the quantity of water used in the home.

The convention in designing a rural water supply scheme in an underdeveloped country, however, is to follow precisely the procedure developed for use in industrialized countries, ignoring these major systemic differences. Thus, for instance, the engineer just assumes some arbitrary figure to be the ''requirement'' for water. (WHO recommends 30 liters per capita per day as the minimum, while others have recommended 50 liters per capita per day; McJunkin, 1983.) No account is taken of the fact that demand may not reach, or alternatively may exceed, this ''requirement,'' and no systematic account is taken of the fact that by increasing the quantity of water that will be used, health may be improved.

Incorporating household behavior into the design process

Data from around the world suggest that the quantities of water used for domestic purposes vary considerably from culture to culture and from group to group within any particular society. Furthermore, field studies in rural Africa suggest that the demand for water is inelastic with respect to distance over a certain range, but elastic when the distance is greater than about 1 kilometer (White et al., 1972; Feachem et al., 1978).

It is thus incorrect to assume, in any particular setting, that there is a "standard requirement" for water. The critical policy question, however, is not whether the conventional procedure is correct or not, but whether the cost of being incorrect is sufficiently great to justify the collection and analysis of additional data and the modification of conventional design procedures.

To indicate how one might go about specifying this cost of using incorrect demand information, consider the following simple didactic model for the design of a rural water supply project.

The objective of the rural water supply project is to maximize health benefits. It is assumed that there is a monotonic relationship between health benefits and the quantity of water used by the population for domestic purposes, a reasonable assumption in many rural communities (White et al., 1972). A limited sum of money is available for constructing the project. The source works are already in existence, and the source is capable of providing more water than can be used by the community to be served.

The dilemma faced by the engineer is that there is a direct trade-off between the design capacity of the system and the distance at which water can be supplied. That is, if the engineer chooses to build a system that is capable of supplying large quantities of water, the standposts are going to be far from the homes of the villagers, while if he chooses to build a system that delivers less water, the water can be provided closer to the home.

The problem can be formulated in a mathematical model:[2]

Objective: Maximize Q
Subject to:

(1) behavior constraint: $Q = \alpha_1 S^{\beta_1}$; and
(2) budget constraint: $K \geqslant \alpha_2 S^{\beta_2} Q^{\beta_3}$

where

Q = total consumption of water,
S = distance from household to standpost,
K = available resources,

and the αs and βs are parameters estimated from field data.

If complete and precise information is available on both behavioral and cost relationships, the "optimal" values of the design parameters can be calculated and two different types of "sensitivity analyses" carried out. First, the effect of including behavioral information in the design procedure can be assessed by calculating the quantity of water actually used when the design procedure takes account of the information on the relationship between distance and demand for water, and comparing this quantity with the quantity of water used when the conventional method is applied. Second, assuming that detailed demand information is to be incorporated into the design process, the model can be used to determine the sensitivity of the quantity of water actually used to errors in the parameters of the behavioral and cost relationships. In this way, information is gleaned on the value of collecting additional data on each of the parameters. Where the output is insensitive to a particular parameter, a coarse estimate of that parameter will suffice; where particularly sensitive parameters are identified, subsequent research efforts and data collection exercises should concentrate on obtaining precise estimates of these particular parameters.

For a range of "standard water requirements" (all of which have been advocated in the technical literature) the inefficiencies due to neglect of the actual demand information are presented in Table 1. The usefulness of collecting detailed demand data and incorporating these into the design process obviously cannot be assessed definitively with so simple a model. Nevertheless, the model suggests that incorporating such demand information leads to substantially higher estimates of the quantities of water used by the population than if such data are ignored. That is, the model suggests that the validity of design decisions is seriously impaired by the conventional practice of ignoring the elasticity of demand with respect to distance.

TABLE 1 The effect of simple demand assumptions on water use

	Optimal design	Assumed requirement[a]		
		15	30	50
Distance to standpost	1,430	1,170	2,680	4,950
Liters of water used per capita per day	17.9	15.0	14.8	12.3
Percent reduction in consumption due to inefficient design	0	16	17	31

[a] Liters per capita per day.

Assuming that demand information is to be incorporated into the design procedure, the question arises as to the amount of effort that should be expended on estimating the parameters of the behavior and cost functions. To answer this question, the second sensitivity analysis is carried out as follows.

The value of more precise information on any particular parameter, say

β_1, may be determined by comparing the quantity of water that will be consumed when the system is designed using the true value of β_1 with the quantity of water that will be consumed when the system is designed using an estimated value of β_1, namely, $\hat{\beta}_1$. That is:

$$\text{Loss of efficiency} = \frac{Q(\beta_1) - Q(\hat{\beta}_1)}{Q(\beta_1)}$$

In Table 2 the inefficiencies due to 10 percent over- and underestimates of each parameter value are presented.[3] As before, no definitive conclusions on the relative importance of information on the different parameters can be drawn from so simple a model. Nevertheless, it appears that the inefficiencies due to errors in estimates of some behavioral and cost parameters can be serious, and, second, precise estimates of the parameters in the exponents of the behavioral and economic functions (i.e., the βs) appear to be more important than precise estimates of the scaling parameters (i.e., the αs). Since engineers have devoted a great deal of attention to the estimate of cost functions, the errors in the cost parameters are likely to be relatively small. The errors in the behavioral parameters, however, are likely to be much larger and much more serious.

TABLE 2 Reduction in quantity of water actually used due to errors in parameter estimates

	Percent reduction if parameter value is	
Parameter	**Underestimated by 10 percent**	**Overestimated by 10 percent**
Behavioral		
α_1	8	3
β_1	6	14
Cost		
α_2	2	4
β_2	16	6
β_3	9	22

This example has several implications. First, the model strongly suggests that the validity of decisions made in designing rural water supply projects is seriously affected by the conventional engineering approach toward estimating required system capacity. Specifically, the model suggests that "standard water requirements" should not be used in designing these systems, but that detailed information should be collected on the effect of distance on demand and such information incorporated into the design procedure.

Second, the model indicates that the inefficiencies resulting from errors in the parameter estimates can be substantial, implying that detailed data should be collected on actual water demand functions in any specific area in which a water supply program is planned. The cost of such data collection is not likely to be great, while the benefits of incorporating such information into the design procedure appear to be substantial.

Incorporating epidemiological considerations into the design procedure

Bradley's classification scheme, by directing attention to the relationship between quantity of water used and health, demanded that health considerations be restored to a central role in the design process. Over the past ten years some attention has been given to ways of doing this. The emphasis has been on trying to define ''threshold values'' beyond which further increases in the quantity of water used have little impact on health, and in using such values to define ''targets'' for water use.

Several problems have arisen in the course of this work. Different analysts have arrived at quite different target requirements, varying from 15 liters per capita per day (lcd), to 20–30 lcd, to 50 and even 60 lcd (Cuny, 1983; Hughes, 1983; McJunkin, 1983; Bannaga et al., 1978, respectively).

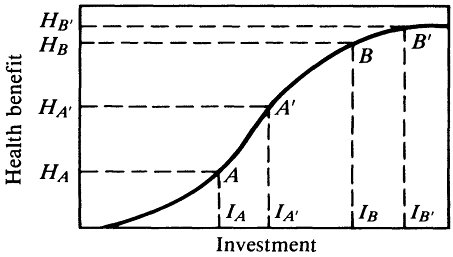
There are serious problems, moreover, not just with the definition of a ''magic number,'' but with the behavioral, epidemiological, and decision-making assumptions implicit in such efforts. Because of the great importance of finding ways of translating this epidemiological knowledge into practical and appropriate guidelines for the design of water supply systems, these problems and some tentative steps toward solving them are outlined.

First, the behavioral problem. As indicated earlier, it is insufficient to simply specify that the capacity of a system should be such that the population served can draw a ''target'' amount of water from the system each day, even if that target is based on sound epidemiological data. It is essential that the determinants of water usage by any particular population be understood, and that such knowledge be used in designing the water supply system.

Second, the epidemiological problem. The most obvious difficulty with operationalizing the water quantity–health concept in any particular area is that it is prohibitively expensive and difficult to carry out the required epidemiological studies in every such area. For this reason there have been attempts to define, using existing epidemiological studies, ''target'' water use figures at which water-washed diseases (i.e., those diseases the prevalence of which is affected by the quantity of water used for personal hygiene) are greatly reduced. Yet, of all of the epidemiological studies on this issue, not one has collected data on the quantities of water used for personal hygiene, the explanatory variable in Bradley's scheme. Rather, surrogates have been used—most commonly, distance to the water source and total quantity of water used for domestic purposes. This use of surrogates without validation of the relationship between the surrogate and the explanatory variable may well account for the large variation observed in the overall levels of water usage necessary to reduce the incidence of water-washed diseases. Because water-use habits are an integral part of an overall pattern of culture, the quantity of water used for hygienic purposes by, for example, a family that uses 15 lcd in the New Guinea Highlands may be quite different from the quantity of water used for hygienic purposes by a Bengali family that uses the same overall amount of water.

Third, there are decision-theoretic problems with the present method of incorporating epidemiological considerations into the procedures for allocating resources in the water sector. As indicated earlier, the consensus of analysts interested in this problem is that water supplies should be designed to provide water to a threshold level beyond which there are no further reductions in water-washed diseases. Indeed it has been argued that it may be better to supply fewer people at the threshold level than to spread resources around so that more people can be supplied at a lower level (Shuval et al., 1981). This decision-making process is examined using Figure 1, which shows the hypothetical relationship between investment in water supply and health benefits.

FIGURE 1



A quantity of money is available either to improve the water supply to a community from level A to level A', or to ensure that a second community's supply is improved from level B to the "threshold level," B'. The proponents of the threshold theory would argue that the effectiveness of the investment, measured in health terms, would be maximized by ensuring that community B was moved to the threshold level. Given the relationships shown in Figure 1, this would be an incorrect decision, since $(H_{A'} - H_A) > (H_{B'} - H_B)$. In more general terms this example suggests that the whole notion that supplies must be built so that at least the threshold level of supply is available to the communities served is incorrect, and that the correct decision rule is rather the economist's rule, namely of targeting investments to those communities where the marginal benefit of the investment is greatest.

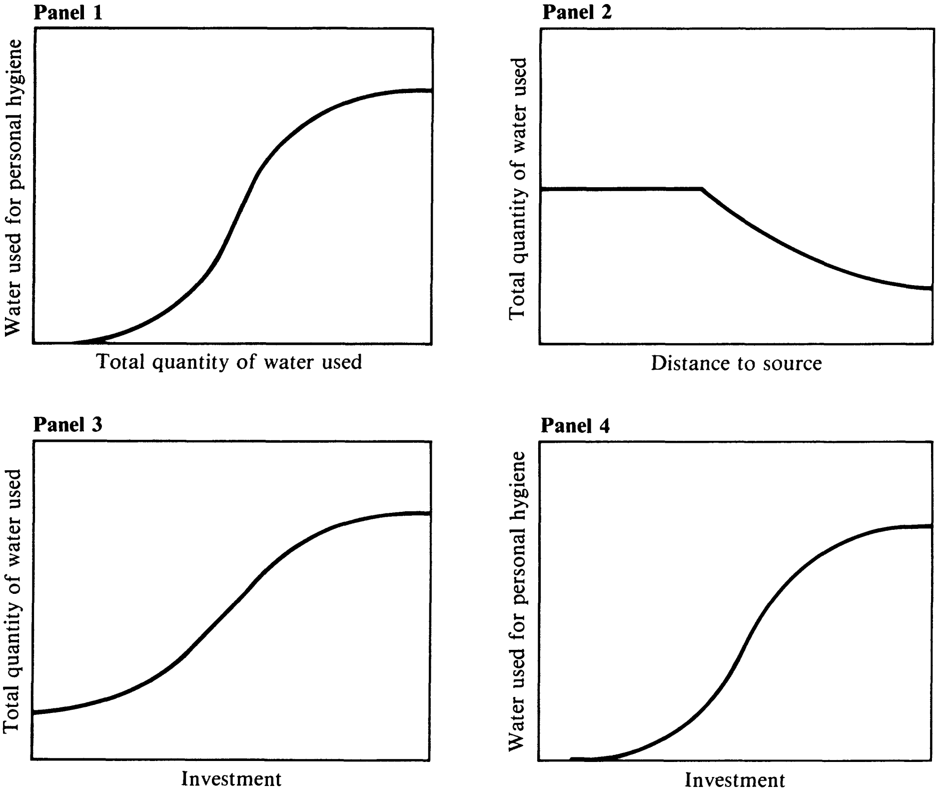
The fact of the matter, then, is that while most water supply planners in underdeveloped countries recognize the desirability of including epidemiological factors into the resource allocation and design procedures, in the absence of sound practical methods for doing so, these considerations are largely ignored in practice. In light of these many difficulties is there any way to transform the conceptual framework implicit in the above discussion into a set of practical procedures to be used by planners and designers?

One procedure might be to develop detailed information on the effect of investments in water supply programs on health in each of the potential project areas. However, there are serious methodological difficulties with such an approach (Briscoe, 1984). Measurement of the direct effect of the investment ignores the degree to which the investment affects the health impact of subsequent, complementary programs. Furthermore, the scale and complexity of the required field studies make this option impractical.

A feasible alternative is to try to operationalize Bradley's explanatory variable, "the quantity of water used for hygienic purposes." It is more difficult to measure this disaggregated variable than to measure the total quantity of water used for domestic purposes. Upon closer examination, however, this does not appear to be an insuperable difficulty, and the following is proposed as a first step in developing a practical operational procedure.

In any area in which water supply programs are being considered, two baseline behavioral studies would be carried out. First, the relationship between the quantity of water used for hygienic purposes and the total quantity of water used for domestic purposes would be specified (as in Panel 1 of Figure 2). Second, the relationship between distance to the source and the total quantity of water used would be specified (Panel 2). Using the infor-

FIGURE 2 Conceptual model for measurement of investment decisions related to water supply programs



mation in Panel 2, the engineer would determine the relationship between the level of investment and the total quantity of water used (as in Panel 3). Then, combining the information of Panels 1 and 3, the engineer would develop a curve relating the quantity of water used for personal hygiene to the level of investment (as in Panel 4). Then, rather than trying to compare investment opportunities by comparing the marginal effect of investments on health, the marginal effect of investments on the quantity of water used for hygienic purposes may be used.

The use of this surrogate appears to be defensible on both theoretical and practical grounds, and the procedure outlined would appear to represent a reasonable first step in incorporating epidemiological considerations into the planning and design of water supply projects in underdeveloped countries. In the medium and long run, of course, it is essential that the validity of the choice and use of this surrogate be tested in several settings and that the necessary procedural adjustments be made as the findings of such research become available.

Conclusions

This paper illustrates some generic concerns with the conceptual frameworks used in research on child survival by examining these concerns in a specific sector, namely the water sector. This analysis is based on two major premises. First, it is assumed that the water sector has a significant role to play in reducing child and other mortality in underdeveloped countries. Second, it is assumed that this role can be carried out efficiently only if the resource allocation and design procedures used in underdeveloped countries are based on an assessment of the problems faced in these countries, and not by adopting willy-nilly the procedures developed to deal with sanitary engineering problems in the quite different setting of the industrialized countries.

A striking general conclusion from the analysis presented in this paper is that, if the effectiveness of water supplies in enhancing health in underdeveloped countries is to be maximized, the priority area of research is the development of methods for collecting and analyzing data on water-use behavior and on methods for incorporating this information into planning and design procedures.

This research must necessarily be carried out by an interdisciplinary team. Anthropologists, social psychologists, and other behavioral scientists will play an important role in identifying the factors that affect water-related behavior. Economists will play a central role, for the major objective of the research would be to collect data on behavior and to deduce, from these data, the effect of each factor that affects choice. Sanitary engineers, too, would play a central role, since the ultimate product of such research must be a set of planning and design procedures that will be implemented primarily by these professionals, who have traditionally been encharged with these tasks. And, finally, health educators would play a central role given their task of developing the ''software'' components of water supply projects.

Although the analysis in this paper has focused on the need to expand the conceptual framework used by sanitary engineers, similar analyses could be undertaken for many other areas that are likely to play a role in increasing child survival in developing countries. In developing expanded immunization programs, for instance, the critical constraints are not strictly problems of medical technology but are those that deal with the effectiveness of the delivery systems and the utilization of the available services by the population (Foster, 1984). In sum, as stated by Tekçe and Shorter (1984), a critical task in formulating effective strategies for improving child survival in developing countries is "to recapture and reformulate the early concerns with the social aspects of health and disease" in light of the conditions prevailing in the developing countries of today.

Notes

1 An outstanding example of this occurrence is Darwin, a man who had no more than a rudimentary understanding of physical and chemical principles but who was, nevertheless, able to produce a new and higher level of understanding of material phenomena. This understanding had eluded those much better schooled than he in the physical and chemical principles that biology both incorporated and transcended.

2 Solution of the model: Since both constraints will be binding, the optimization problem can be solved using Lagrange's method, i.e.,

$$L(Q,S,\lambda_1,\lambda_2) = Q + \lambda_1(Q - \alpha_1 S^{\beta_1}) + \lambda_2(K - \alpha_2 S^{\beta_2} Q^{\beta_3})$$

and

$$\frac{\partial L}{\partial Q} = 1 + \lambda_1 - \beta_3 \lambda_2 \alpha_2 S^{\beta_2} Q^{\beta_3 - 1} = 0$$

$$\frac{\partial L}{\partial S} = -\beta_1 \lambda_1 \alpha_1 S^{\beta_1 - 1} - \beta_2 \lambda_2 \alpha_2 S^{\beta_2 - 1} Q^{\beta_3} = 0$$

$$\frac{\partial L}{\partial \lambda_1} = Q - \alpha_1 S^{\beta_1} = 0$$

$$\frac{\partial L}{\partial \lambda_2} = K - \alpha_2 S^{\beta_2} Q^{\beta_3} = 0$$

Solving the 4 simultaneous equations in 4 unknowns, the optimal values of the design variables are found to be:

$$S^* = \left(\frac{K}{\alpha_1{}^{\beta_3}\alpha_2}\right)^{\frac{1}{\beta_2 + \beta_1\beta_3}}$$

and

$$Q^* = \alpha_1\left(\frac{K}{\alpha_1{}^{\beta_3}\alpha_2}\right)^{\frac{\beta_1}{\beta_2 + \beta_1\beta_3}}$$

It is assumed that the supply will serve 1000 people, that $15,000 is available for the project, and that the parameter values are

$$\begin{aligned} \alpha_1 &= 158 \times 10^3 \\ \beta_1 &= -0.30 \\ \alpha_2 &= 1600 \\ \beta_2 &= -0.5 \\ \beta_3 &= 0.6 \end{aligned}$$

For these values, $S^* = 1430$ meters and $Q^* = 17{,}900$ liters/day $= 17.9$ lcd

Some typical values for calibrating the mathematical model are:

Behavior Empirical data from East Africa (White et al., 1972) suggest that the effect of distance on water use is of the form shown in Figure 2. It is assumed that for the 1000 people: $Q = 20 \times 10^3$ l/d for $S \leq 1000$ m and $Q = 158 \times 10^3 S^{-0.3}$ l/d for $S > 1000$ m (whence $Q = 10 \times 10^3$ l/d at $S = 10{,}000$ m).

Costs (a) The effect of scale: For water distribution systems a typical scaling factor is $\beta_3 = 0.6$ (Thomas, 1971). (b) The effect of density of standposts: Under a set of simplifying assumptions it can be shown that a reasonable value for $\beta_2 = -0.5$, which implies that, for a given supply, as the average distance to a standpost is halved the cost of the distribution network increases by 41 percent.

Average cost A representative cost for a rural water supply delivering 20 lcd is $20 per capita (Saunders and Warford, 1976). Calibrating the cost equation thus yields a value of $\alpha_2 = 1600$.

3 Procedure for determining the cost of incorrect parameter estimates:

(a) Using the incorrect value of the estimated parameter and the correct values of all other parameters, values of S_{design} and Q_{design} are estimated from:

$$S_{\text{design}} = \left(\frac{K}{\alpha_1{}^{\beta_3}\alpha_2}\right)^{\frac{1}{\beta_2+\beta_1\beta_3}}$$

and

$$Q_{\text{design}} = \alpha_1 S^{\beta_1}$$

These are the design parameters on which the system design is based.

(b) When the system is actually constructed, however, it is found that after the system of capacity Q_{design} is laid to S_{actual} the funds are exhausted, where

$$S_{\text{actual}} = \left(\frac{K}{\alpha_2 \hat{Q}^{\beta_3}}\right)^{\frac{1}{\beta_2}}$$

calculated with the true parameter values.

(c) At this actual distance, S_{actual}, the demand for water will be

$$Q_{\text{demand}} = \alpha_1\, S_{\text{actual}}^{\beta_1}$$

calculated with the true parameter values.

(d) The amount of water actually used will be the lesser of the design flow (Q_{design}) and the demand (Q_{demand}).

References

Ackerknecht, E. H. 1953. *Rudolf Virchow*. Madison: University of Wisconsin Press.

Bannaga, S. E. I., and J. Pickford. 1978. "Water-health relationships in Sudan," *Effluent and Water Treatment Journal* 18: 559–569.

Bradley, D. J., and P. Emurwon. 1968. "Predicting the epidemiological effects of changing water sources," *East African Medical Journal* 45: 284–291.

Briscoe, J. 1984. "Intervention studies and the definition of dominant transmission routes," *American Journal of Epidemiology* (in press).

Chadwick, E. H. 1982. *Report of the Sanitary Condition of the Labouring Population of Great Britain,* 1965 edition. Edinburgh: Edinburgh University Press.

Craun, G. F., and L. J. McCabe. 1973. "Review of the causes of water-borne disease outbreaks," *Journal of the American Water Works Association* 65: 74.

Cuny, F. C. 1983. "Development of water supply standards for refugee camps." Dallas: Intertect.

Engels, F. 1845. *The Condition of the Working Class in England in 1844*. Palo Alto: Stanford University Press.

Feachem, R. G., E. Burns, S. Cairncross, A. Cronin, P. Cross, D. Curtis, M. K. Khan, D. Lamb, and H. Southall. 1978. *Water, Health and Development: An Interdisciplinary Evaluation*. London: Tri-Med.

———, D. J. Bradley, H. Garelick, and D. Mara. 1981. *Health Aspects of Excreta and Sullage Management—A State of the Art Review,* No. 3 in series on Appropriate Technology for Water Supply and Sanitation. Washington, D.C.: World Bank.

Foster, S. O. 1984. "Immunizable and respiratory diseases and child mortality," in this volume.

Geertz, G. C. 1966. *Agricultural Involution: The Process of Ecological Change in Indonesia*. Berkeley: University of California Press.

Hazen, A. 1914. *Clean Water and How to Get It,* 2nd ed. New York: Wiley.

Howe, C. W., and F. P. Linaweaver, Jr. 1967. ''The impact of price on residential water demand and its relation to system design and price structure,'' *Water Resources Research* 3, no. 1: 13–32.

Hughes, J. M. 1983. ''Potential impacts of improved water supply and excreta disposal on diarrheal disease morbidity: An assessment based on a review of published studies,'' draft manuscript for publication. Atlanta: Centers for Disease Control.

Koch, R. 1894. *Professor Koch on the Bacteriological Diagnosis of Cholera, Water Filtration and Cholera, and the Cholera in Germany during the Winter of 1892–3*. Edinburgh: David Douglas, Publisher.

McJunkin, F. E. 1983. *Water and Human Health,* 2nd ed. Washington, D.C.: National Demonstration Water Project.

McKeown, T., R. G. Brown, and R. G. Record. 1972. ''An interpretation of the modern rise of population in Europe,'' *Population Studies* 26, no. 3: 345–382.

Mara, D. D. 1976. *Sewage Treatment in Hot Climates*. New York: Wiley.

Maxcy, K. F., ed. 1941. *Papers of Wade Hampton Frost, M.D., A Contribution to Epidemiological Methods*. New York: Commonwealth Fund.

National Academy of Sciences. 1977. *Drinking Water and Health,* Vol. I. Washington, D.C.: National Academy of Sciences.

National Demonstration Water Project. 1978. *Drinking Water Supplies in Rural America*. Washington, D.C.: National Demonstration Water Project.

Saunders, R. J., and J. J. Warford. 1976. *Village Water Supply: Economics and Policy in the Developing World*. Washington, D.C. and Baltimore: World Bank and Johns Hopkins University.

Sedgewick, W. T., and J. S. MacNutt. 1910. ''On the Mills-Reinke Phenomenon and Hazen's Theorem concerning the decrease in mortality from diseases other than typhoid fever following the quantification of public water supplies,'' *Journal of Infectious Diseases* 7, no. 4: 489–564.

Shuval, H. I., R. L. Tilden, B. H. Perry, and R. N. Grosse. 1981. ''Effect of investments in water supply and sanitation on health status: A threshold-saturation theory,'' *Bulletin of the World Health Organization* 59, no. 2: 243–248.

Snow, J. 1854. *On the Mode of Communication of Cholera,* ''Second edition, much enlarged.'' London: Churchill. Reprinted by the Commonwealth Fund, New York, 1936.

Tekçe, B., and F. C. Shorter. 1984. ''Determinants of child mortality: A study of squatter settlements in Jordan,'' in this volume.

Thomas, H. A., Jr. 1971. ''Sensitivity analysis of design parameters of water resource systems.'' Cambridge, Mass.: Division of Applied Sciences, Harvard University.

White, G. F., D. J. Bradley, and A. U. White. 1972. *Drawers of Water, Domestic Water Use in Africa*. Chicago: University of Chicago.