COMMUNITY WATER SUPPLY BRANCH

AGENCY FOR INTERNATIONAL DEVELOPMENT

REPORT ON
WATER DEMAND STUDY

INTERNATIONAL PROGRAM IN SANITARY ENGINEERING DESIGN
UNIVERSITY OF NORTH CAROLINA
CHAPEL HILL, N.C.
1969

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1. INTRODUCTION

Early in 1967, staff members of the Regional School of Sanitary Engineering at San Carlos University in Guatemala decided to conduct a community water demand study. This decision was based on the suspicion that new water supply systems throughout the country were being improperly sized. In general, little data are available in Guatemala (and most developing countries) for planning purposes, which result in per capita water demand design values being largely based on value judgement. Although the original goal of the study included accurate determination of water demands, the long range objective was development of a basis for optimal sizing of supply systems which includes considerations which go beyond the matter of demand.

In June, 1967, Engineer Octavio Cordon of San Carlos University traveled to the United States for a short visit which included a trip to the University of North Carolina. One of the objectives of Cordon's visit was to meet with Dr. F. Pierce Linaweaver in order to discuss the proposed water demand study. Dr. Linaweaver had recently completed an extensive and similar study in the United States, and Cordon wanted to investigate the possibility of Linaweaver's participation in the Guatemala work. During Cordon's visit at UNC, he learned of interest among staff members associated with the International Program in Sanitary Engineering Design in a water demand study similar to that proposed for Guatemala. Like the Guatemalans, the IPSED group was concerned with optimal design of water supplies. As a result, it became apparent that IPSED could probably cooperate with the Guatemalans to mutual advantage, and therefore, Mr. Donald Lauria of the International Program at UNC accompanied Engineer Cordon on his visit to Washington to discuss the proposed study with Dr. Linaweaver. At the time of this trip, plans were made for both Linaweaver and Lauria to visit Guatemala in September as consultants to the Regional School, and a brief visit was also made to the Community Water Supply Branch of AID to discuss the proposed study and the possibility of AID's involvement in this work.

The duration of the September field visit to Guatemala was approximately two weeks during which time more definite plans were made for conduct of the study. It was decided that the work would be performed in three stages. The first stage was scheduled for commencement early in 1968, and duration was tentatively set at one year. The main objective of this initial phase was to demonstrate practicability of the study and develop required equipment, procedures, and methodology. Less interest was expressed in the usefulness of basic data which would be obtained in the two or three small study communities.

Broad objectives were also adopted for the second and third stages of the study. The second stage was to commence in 1969, and its purpose would be to obtain information on water demands in as many communities as possible. These data would be sought in order to provide a more solid foundation for sizing new water systems throughout the country. During this stage, it was agreed that, if possible, the water demand study would be exported to other Central American countries. Although a firm duration period for the second stage was not set, it was thought that this work would take approximately two years, or perhaps somewhat longer. Toward the end of this period, it was anticipated that there would be gradual transition to a third stage which would include evaluation of the components of demand and its variation.

During the September field visit, several prospective communities for inclusion in the study were visited and plans were made to purchase and install metering equipment which included propeller-type master meters, level recorders for use in storage reservoirs, and special recorders for individual house meters. It was also decided that students from the University would do most of the basic work on collecting and analyzing data during this first stage. At the completion of the field visit, summary reports were prepared by Dr. Linaweaver and Mr. Lauria, copies of which were included in Appendix A of this report.

Following the June visit to AID, there was intercommunication between the Community Water Supply Branch and the International Program in Sanitary Engineering Design regarding involvement of AID in the water demand study. A scope of services for the study was proposed by IPSED, and these included: (1) consultation with members of the Sanitary Engineering staff at San Carlos University regarding the study, (2) assistance with collection and analysis of water usage and other data, (3) continual liaison and consultation with the Guatemalans during the first stage, and (4) presentation of findings to the Community Water Supply Branch. After some discussion, these services were included in a formal Task Order proposal which was submitted to AID and subsequently approved. This report is submitted in accordance with that Task Order.

2. BASIC WATER SUPPLY PLANNING PROBLEMS

The Guatemala demand study is largely based on the following question which must be answered in order to design water supplies: what shall be the scale of the system? The traditional approach of sanitary engineers to this question has been to set project scale equal to the quantity (Q_o + qpx) where "Q_o" is the existing unserved rate of water demand, "q" is the per capita rate of water demand at the end of design period "x", and "p" is the arithmetic population growth rate (or population equivalent). If it is assumed that the capacity of water supply facilities must always equal or exceed demand, then design period "x" is the expected period of excess capacity following construction of the system. That is, "x" is the time it takes for demand to grow equal to supply capacity following expansion. Under this assumption, capacity expansion is generally made at the time when Q_o is zero. If expansion is made before demand has grown equal to supply (i.e., at a time of existing excess capacity), then Q_o is negative.

Sanitary engineers have, wherever possible, adopted design standards in regard to "q" based on actual water usage data. The problem in Guatemala and with most of the developing countries of the world is that data upon which "q" can be based are lacking, and hence "q" is often selected by value judgement with little basis in fact. Hence, we see that the primary objective of the water demand study is to obtain a factual basis for "q", thereby leading to more accurate sizing of water supplies.

The other parameters upon which water supply design depends include "x" and "p". Where historical population data are lacking, determination of "p" presents real problems. In such cases, judgements are often made about population growth in communities to be served. For example, in many countries it is assumed that population grows at a rate between two and five percent per year. Of course, where data exist, "p" is obtained by projection of actual population records.

Determination of "x" is usually a matter of value judgement. In general, sanitary engineers have adopted design standards regarding "x" for different types of facilities under design. For example, water treatment plants and supply works are often designed for periods in the range of ten to twenty-five years. In any event, it is apparent that system scale depends not only on per capita demands "q", but also on "x" and "p", and information on all three parameters is needed for proper design. Until recently, there was little rationale for "x", and "p" required historical data records. Consequently, the logical first step toward improved water supply design included rigorous determination of "q", which is the course of action adopted in the Guatemala study.

3. MATHEMATICAL MODELS FOR OPTIMAL DESIGN

As mentioned in Section 2 above, sanitary engineers have for some time adopted standards which permit sizing of water supply systems. For the most part, such design standards were developed for use in the economically advanced countries. Within recent years, the rationale of these standards has been seriously questioned, and the translation of these standards for use in developing countries has come under sharp attack.

Such is the case not only in the field of sanitary engineering but in the process industries in general. As a result, researchers have been working toward development of a rational basis for determining the optimal scale of systems. Some of the earliest work on this subject was done by Chenery (1952) who developed a mathematical model for expansion scale. Chenery's work was expanded by Manne (1961, 1967) which in turn was further developed by Muhich (1966). Other workers included Lynn (1964), McDowell (1960), White (1961), English (1968) and Klein (1968). Although there are differences among the models of these workers, the models of Manne seem to be most appropriate to the problem of optimal water system sizing which lies at the root of the water demand study, and hence these models will be presented in this section as a theoretical basis for the field work in Guatemala.

Manne has developed two basic models. In the first, called the "no-backlogs model", it is assumed that the supply capacity of facilities must always equal or exceed demand. In the second model, this restriction is relaxed, demand sometimes being allowed to exceed capacity (i.e., demand being "backlogged"). In both models, Manne develops the conditions for optimal timing and scale of system construction by use of classical methods.

3.1 No Backlogs Model

Assume (1) demand grows linearly over time with no uncertainty at some constant rate D (say D = mgd/yr), (2) time horizon is infinite, (3) capacity expansion is made when demand equals capacity (i.e., when excess capacity is zero), (4) capacity expansions are implemented instantaneously, (5) initially demand equals capacity, and (6) costs and discount rate remain constant over time.

Graphical representations of demand and capacity expansions are shown in Figures 3.1 and 3.2.

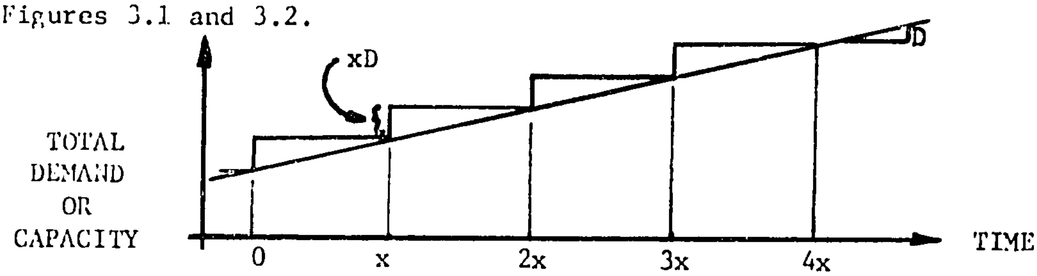

FIGURE 3.1

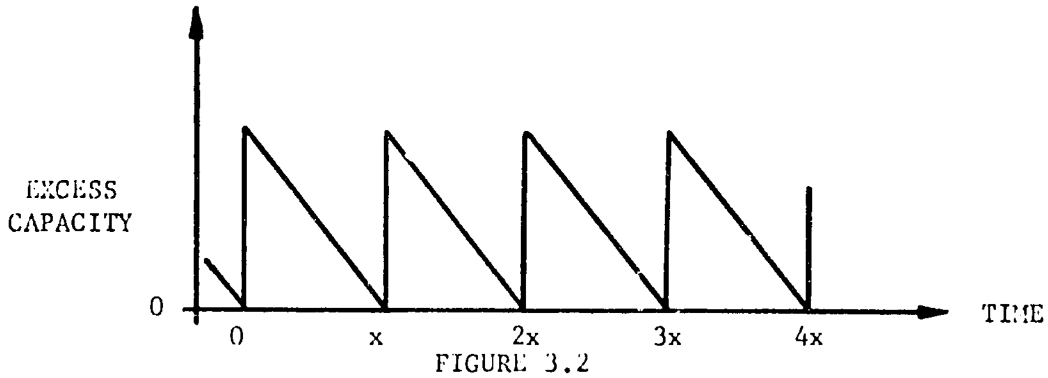

FIGURE 3.2

From assumptions (1) and (6) above, we may conclude that the design period, x, for every expansion is constant since the future from every point of zero excess capacity is identical. Hence, an optimal decision at one such point is optimal at every other such point.

Assume that the cost of a capacity expansion, C(xD), exhibits increasing returns to scale, in which case the following cost function applies.[1]

$$C(xD) = k(xD)^a \tag{3.1}$$

where $k > 0$ is the cost of one unit (say, one mgd) system and $0 < a < 1$ is the economy of scale factor

Define $C(x)$ = present value of all future costs from any point of zero excess capacity,

$$= k(xD)^a + C(x)e^{-rx} , \tag{3.2}$$

where r is the discount rate.

Solving Eqn. (3.2) for C(x), we obtain the present value of future costs from time zero to infinity

$$C(x) = k(xD)^a/(1-e^{-rx}) \tag{3.3}$$

Assuming the planning problem is to minimize present value costs, we seek the optimal design period, x*, or optimal expansion scale x*D, for which C(x) is minimal which can be found by setting $dC(x)/dx=0$. The resulting optimality condition is

$$a = rx^*/(e^{rx^*} - 1) \tag{3.4}$$

In the optimality Eqn. (3.4), it should be noted that the design period, x*, is a function of only "a", the economy of scale factor and "r", the discount rate. Hence, the rate of demand increase (D), the basic cost of a one mgd system (k), and the length of the planning period (i.e., the number of expansions to be made) have no effect on the optimal design period. It should also be noted that as "a" decreases, the optimal design period increases. Small values of "a" indicate large economies of scale. (We know intuitively that there are greater economies of scale in pipeline construction than in say, treatment plant expansion. Hence, for years sanitary engineers have designed water supply and treatment works for shorter periods than distribution systems). We also note from Eqn. (3.4) that as "r" decreases, optimal design period increases. But the discount rate in developing countries is relatively high compared to the economically advanced ones. Hence, it follows that design periods should be somewhat shorter abroad than in the U.S. A cross plot of Eqn. (3.4) is shown in Figure 3.4.

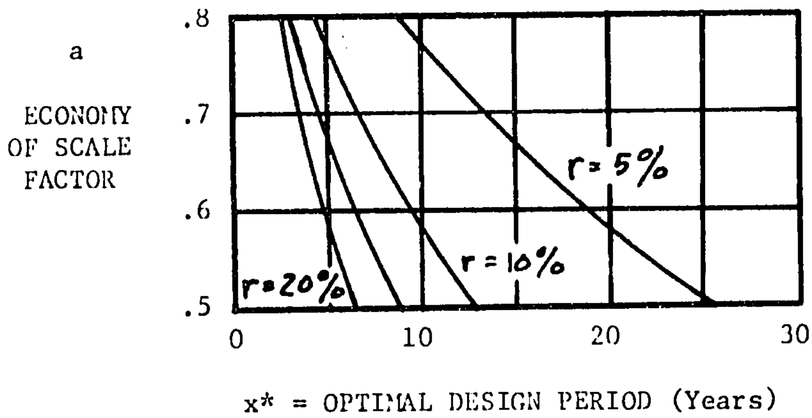

FIGURE 3.4

3.2 Backlogs Considered

The assumptions of the no-backlogs model are retained with the following exceptions: (1) instead of expanding when excess capacity is zero (assumption 3, demand is allowed to rise above capacity. Excess demands may be satisfied by either importing or backlogging (i.e., letting demand go unsatisfied), (2) the constant importing (or backlogging) price is "p" (say, p = dollars per gallon). More generally, "p" is called the backlogging penalty price.

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1 With increasing returns to scale, costs increase at a decreasing rate as scale increases. The graphical representation of the cost function Eqn. 3.1 is as follows

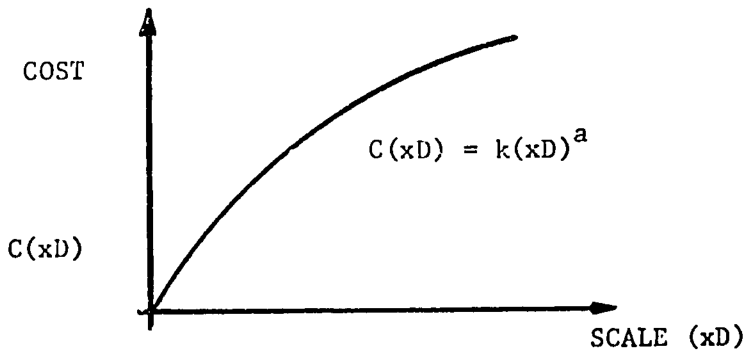

FIGURE 3.3

A graphical representation of demand and capacity expansion is shown in Figure 3.5.

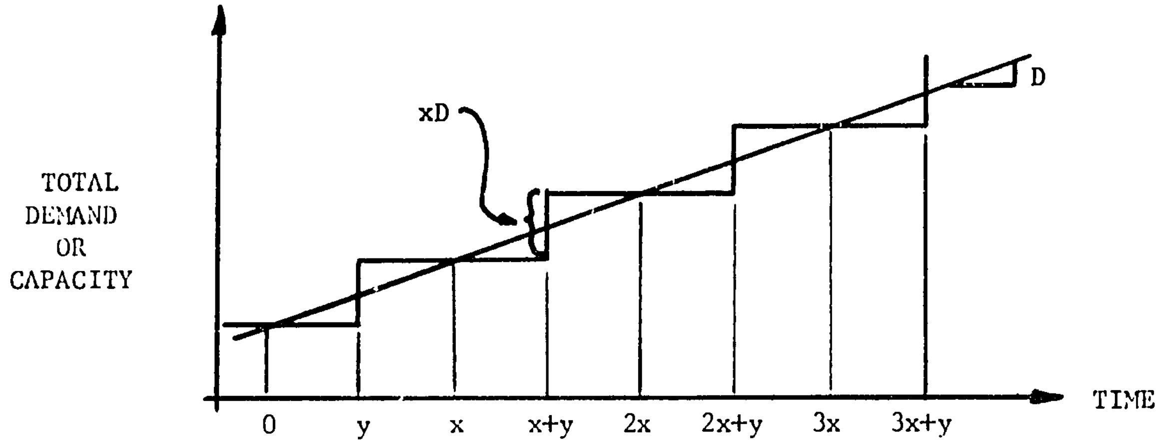

FIGURE 3.5

At any time, t, in the first backlog period ($0 < t < y$), the rate of unsatisfied demand is "Dt". The units of "Dt" in the water supply field are volume per unit time, say mgd or gallons per year. Using the penalty price (p), the rate at which costs acrue at time "t" is "pDt", with units such as dollars per day or dollars per year. If "p" represents the price of importing water from a neighboring community, then "pDt" is the rate at which importing charges acrue at time "t". On the other hand, if water is not imported and demands actually go unsatisfied, then "p" is the "social price" of not having water, in which case "pDt" is the rate at which social costs acrue at time "t". The present value of this cost rate is obtained by discounting to time zero which results in the following expression:

$$pDte^{-rt}. \tag{3.5}$$

The total present value cost due to backlogging in the first period may be obtained by summing the costs over time period zero to y, which, in integral form is the following:

$$\int_0^y pDte^{-rt}\, dt = -\frac{pD}{r^2}\,[rye^{-ry} + e^{-ry} - 1] \tag{3.6}$$

As in the no-backlogs model,

define $C(x,y)$ = present value of all future costs from any point of zero excess capacity.

Then we may write

$$C(x,y) = \text{p.v. Backlog Costs} + \text{p.v. First Expansion Cost at Time } y + \text{p.v. All Future Costs at Time } x$$

$$C(x,y) = -\frac{pD}{r^2}\left[rye^{-ry} + e^{-ry} - 1\right] + k(xD)^a e^{-ry} + C(x,y)\, e^{-rx}$$

$$= \left[\frac{1}{1-e^{-rx}}\right] \cdot \left[\frac{pD}{r^2}\left[1-e^{-ry}(1+ry)\right] + e^{-ry}k(xD)^a\right] \quad (3.7)$$

Assuming the objective is to minimize present value costs, we seek the optimal design period, x^* (or optimal scale x^*D) and the optimal backlog period, y^* (i.e., the optimal time of capacity expansion) which can be found by setting the appropriate partial derivatives of Eqn. (3.7) equal to zero. The resulting optimality conditions are

$$y^* = \frac{r\ k(xD)^a}{pD} \quad (3.8)$$

$$a = \frac{x^*/(e^{rx^*} - 1)}{y^*/(e^{ry^*} - 1)} \quad (3.9)$$

Although both Eqns. (3.8) and (3.9) are needed to determine the optimality conditions for the backlogs model, several important observations may be made from Eqn. (3.8).[2] First, by rearranging the equation to the form

$$pDy^* = rk(xD)^a, \quad (3.8a)$$

we note that the left side is the rate at which backlog costs acrue at time y, the time of capacity expansion. The right side is the annual "interest" on construction cost. Hence, we may conclude that expansion should be delayed until backlog costs acrue at the same rate as interest charges.

Secondly, we note that y^* approaches zero when p approaches infinity. But when y^* is zero, we have a case equivalent to the no-backlogs model. The implication here is that as long as p has finite value, then some backlogging is required. In other words, if water may be imported from a neighboring community at some finite price, it never becomes optimal to invoke a policy of no backlogging.

Finally, by rearranging Eqn. (3.8), we may solve for p as follows

$$p = \frac{r\ k(xD)^{a}}{Dy^{*}} \quad . \qquad (3.8b)$$

We have just seen that as y* approaches zero, p approaches infinity. That is, we "impute" the value of infinity to p in the case of no backlogs. More generally, there will be some backlogging of water demand in most developing countries. But we see that (i) the numerator of Eqn. (3.8b) is the "interest" in construction and (ii) the denominator is the rate of unsatisfied demand, both of which usually have known numerical value in developing countries. Hence, by Eqn. (3.8b) it is possible to analyze actual water supply decisions to impute the numerical value of p. That is, it is possible to determine the social costs which are implicitly assigned to not having a public water supply system by analyzing the planning decisions which are actually made.

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2 It should be noted that in the no-backlogs model, only one question was asked, viz, what is optimal scale (or equivalently, what is optimal design period). In that case, the timing of expansion was constrained to equal or exceed demand.
In the backlogs model, there are two questions: (i) what is optimal scale (or design period) and (ii) what is optimal timing for expansion. Hence, there must be two decision variables (x and y) and two optimality equations (3.8 and 3.9).

4. EVALUATION OF COST PARAMETERS

As noted in Section 2, the basic concern of this report is with "qp", the annual rate of demand increase, or equivalently, with "D", using the notation and concepts in Section 3. However, before focusing attention on qp or D, brief concern will be given to the other parameter required for optimal design, viz, the design period, x.

As discussed in Section 3, the optimal design period is a function of two factors, the discount rate, r, and economy of scale parameter, a. The sanitary engineer has little he can do to determine r except rely on the judgement of national economic advisors. In actual practice, what might be done is to use several values of r for determination of the design period and then use judgement to select the one which seems most reasonable (i.e., perform a sensitivity analysis on r). However, the sanitary engineer has much to do with determination of "a", the economy of scale factor which must be evaluated from data on system costs. The question now is what data for which system?

It has already been mentioned that economies of scale differ for water supply, treatment, and distribution systems. In the U.S., "a" for supply and treatment facilities is about 0.65 while for distribution systems it is less than this. Therefore, it becomes necessary to analyze separate cost data for the different types of facilities if separate "a" values are to be determined. What is more is the need to analyze planning cost data to determine the conomies of scale associated with design. It is well known that the amount of effort (i.e., "cost") associated with planning a one mgd system is not much less than that required for a three or five mgd system. Hence there are economies of scale associated with planning just as there are with construction. What one concludes therefore is that there is an optimal planing period for facilities which differs from the construction (or design) period for different types of facilities. These concepts, of course, are not really new since one can find in practice situations where standards have been adopted recommending such different periods. A case in point is Ceylon (Rasiah 1968) where the water supply planning period is 40 to 50 years, the design period is about 20 years, and the construction period is 10 years. The problem now is how to determine 'a", the economy of scale factor?

The general cost function for systems with economies of scale is

$$C = k(X)^a, \quad (4.1)$$

where "X" is system scale and C is system cost. In Section 3, X was seen to be equal to "xD". By taking the logs of both sides, Eqn. (4.1) is transformed to a linear equation

$$\log(C) = \log(k) + a \log(X) \quad (4.2)$$

of the form

$$Y = b_o + b_1 X \quad (4.3)$$

where

$Y = \log(C)$
$b_o = \log(k)$
$b_1 = a$
$X = \log(X)$

Hence, with data on system costs (Y) and scale (X), it is possible to determine the parameters of Eqn. (4.3)(b_1 being the economy of scale factor) by least squares analysis. The least squares equations are

$$b_o = (\Sigma Y)/n - b_1 (\Sigma X)/n, \text{ and} \quad (4.4)$$

$$b_1 = \frac{\Sigma XY - (\Sigma X)(\Sigma Y)/n}{\Sigma X^2 - (\Sigma X)^2/n}, \quad (4.5)$$

n being the number of observations.

5. EVALUATION OF DEMAND PARAMETERS

Using concepts from Sections 2 and 3, optimal scale was seen to be equal to the quantity (qpx*) which is identical to (Dx*). In Section 4, it was shown that x* can ultimately be determined from (i) a least squares analysis of cost data and (ii) the discount rate. Our concern in this section is with the quantity (D), which is the annual rate of demand increase, with such units as mgd per year. As shown above, D is equivalent to (qp), the product of per capita rate of demand and the arithmetic rate of population increase.

In the economically advanced countries where data are abundant and where water demand information is readily available, the problems associated with evaluating "q" and "p" are usually not too serious. Since a large proportion of water supply work is in the nature of expansions rather than new supply, it is usually possible to analyze meter records to obtain indications of per capita demand rates. Similarly, analysis of demographic records provides information on "p" which makes it possible to determine "D", the demand growth rate.

Such is not the case, however, in developing countries. There, systems are generally new and hence historical demand records do not exist. Although some population data may be available, they are often incomplete and sometimes inaccurate. Hence the problems associated with determining "D" are significant.

In practice, what is often done is to use per capita demand rates and population growth rates which have been found to exist elsewhere. Hence one finds, for example, recommendations for "q" of 40 liters per capita per day (lpcd) in the case of public fountains, 100 lpcd in the case of "intermediate stage" design including some house connections, and 200 to 250 lpcd for "final stage" design (Baity 1966). Others have also adopted or recommended similar design standards. Those for Thailand (Panomvan 1968) are in Table 5.1. In addition, the Thais use a three percent annual population growth factor in the absence of actual data. Three percent is also used in Taiwan (1956) together with per capita rates which range from 60 to 200 lpcd, depending on the size of the community served. WHO (1968) recognizes three planning stages for water supplies. In the primary stage when supply is with public fountains, q's of 20 to 30 lpcd are recommended, and where house connections exist, 50 to 80 lpcd. In the intermediate stage, q of 60 to 100 lpcd is recommended and in the advanced stage, q may be over 200 lpcd.

Although many similar design standards could be cited, they all suffer from the same limitations; they are rough estimates which are often inappropriate for specific design situations since the conditions under which the standards obtain are often significantly different from those in the community for which the system is being designed. Indeed, it was suspicion that this case existed in Guatemala which prompted the present demand study.

Recognizing that thumb rules such as the above are often inappropriate, the question is what is to be done about it? The solution, it seems, must include some way of improving demand estimates <u>in the absence of actual data</u>.

TABLE 5.1*

WATER SUPPLY DESIGN STANDARDS IN THAILAND

Population	Design Period (years)	Design Flow (lpcd)
less than 5000	10	60-100
5,000-10,000	10	100-150
10,000-25,000	15	150-200
25,000-50,000	15	200-250
50,000-250,000	15-20	250-300
more than 250,000	20-30	300-400

* Data from "Public Water Supply in Thailand" by Sakoljitt Panomvan, Intl. Conf. on Water for Peace, v 7, p 174, U.S. Govt. Printing Office, Washington, D. C. , 1963.

This, of course, is one of the major goals of the Guatemala demand study, and the methods which are and will be used to obtain this objective include statistical data analysis.

The method of approach is as follows: (i) a hypothesis is made that water demand depends on measurable characteristics of the community. Such characteristics comprise a set of independent variables and demand is the dependent variable. The independent variables may be classified in six categories (see Appendix A); for example, social conditions, economic conditions, environmental conditions, etc. (ii) Based on the hypothesis, a mathematical model is formulated which expresses the interrelationship between independent and dependent variables. For example, if it is hypothesized that demand (assume average daily or maximum daily demand which would be used for design purposes) depends on n independent variables ($X_1, \ldots, X_n$), then the model might be

$$f(X_1, \ldots, X_n) = b_o + b_1 X_1 + \ldots + bX_1 \cdot \ldots \cdot Xn,$$

where f (·) is the quantity demanded.(iii) Having postulated the demand model, the problem now is to find communities or parts of communities with the characteristics of interest <u>and</u> with water supply systems. For example, assume it is hypothesized that water demand depends on three levels of service quality (public fountains, Fordillas, and piped services), three levels of social conditions (bad, medium and good), two economic levels (poor and rich), and two levels of water quality (bad and good), then it would be necessary to find 36 (=3X3X2X2) different communities or parts of communities in order to have a balanced design for evaluation of the model. (iv) Having selected the communities, data would be obtained on both independent and dependent variables in order to evaluate model parameters (the b's) which would be done by regression analysis. (The similarity here with evaluation of the economy of scale factor by least squares analysis should be apparent). (v) With model parameters determined, it should then be possible to use the model for predictive purposes. That is, by measuring community characteristics (the X's) in towns to receive new water supply systems and using these values in the statistical model with numerical b-values, it should be possible to estimate the demand rates for which the system should be designed. The advantage with this approach is, of course, that the design factors are related to the specific characteristics of the communities to be served rather than merely associated with gross characteristics (eg., urban vs rural) which is the general current design practice. (see Appendix B for a report on evaluation of water supply benefits which describes in detail an approach similar to the above).

6. SOME RESULTS FROM GUATEMALA

Some results from the Guatemala water demand study are included in this section. Of significant note are the following:

(i) The overall economy of scale factor (for both supply and distribution) is 0.77 which is relatively large (i.e., small economies of scale).

(ii) Optimal design period is about 5 years with a discount rate of ten percent.

(iii) The Guatemalans have been using a design period of 25 years for water supplies.

(iv) The existing design policy probably results in costs 50 percent greater than if an optimal policy were followed.

(v) The complete reports on water demand in the four Guatemalan towns studied are in Appendix C.

6.1 Water Supply Cost Function

Construction cost data for water supply systems in eleven Guatemalan towns are tabulated below together with town population data

let x = town population in thousands
C(x)= cost of the (entire)system to serve population x

We assume that

$$C(x) = k\,x^{a} \quad , \qquad \text{where} \tag{6.1}$$

k = cost of a system to serve a population of 1000

a = economy of scale factor

By taking the log transform of eqn (6.1) we obtain

$$\log C(x) = \log k + a \log x \tag{6.2}$$

Define log C(x) = Y

$\log k = b_0$

$a = b_1$

$\log x = X$

Hence, eqn (6.2) may be rewritten

$$Y = b_o + b_1 X, \qquad (6.3)$$

which is the linearized predictor eqn. for the cost fn. in eqn (6.1). The parameters of eqn (6.3) may be determined by least squares analysis.

Project No.	$C(x)^{(1)}$	$x^{(2)}$	Y log C(x)	X log x
1	136,150	5.721	5.134	0.757
2	75,460	2.036	4.878	0.309
3	104,000	1.567	5.017	0.195
4	60,244	1.601	4.780	0.204
5	127,100	5.271	5.104	0.722
6	120,500	3.113	5.081	0.493
7	79,000	1.636	4.898	0.214
8	134,400	2.857	5.128	0.455
9	235,540	6.341	5.372	0.802
10	57,270	1.397	4.758	0.145
11	30,956	1.393	4.491	0.144

(1) Water system construction cost in Quetzales
(2) Population served in thousands of persons

$\Sigma X = 4.440$; $\Sigma X^2 = 2.450290$; $(\Sigma X)^2 = 19.7136$

$\Sigma Y = 54.641$; $\Sigma XY = 22.563566$

$$b_1 = \frac{\Sigma XY - (\Sigma X)(\Sigma Y)/n}{\Sigma X^2 - (\Sigma X)^2/n} = \frac{22.563566 - 242.60604/11}{2.450290 - 19.7136/11}$$

$$= \frac{0.508471}{0.658145} = 0.7726 \doteq 0.77$$

$$b_o = (\Sigma Y)/n - b_1 (\Sigma X)/n = \frac{54.641}{11} - \frac{0.7726(4.440)}{11}$$

$$= 4.96736 - 0.31185 = 4.65551 \doteq 4.656$$

——— o ———

$b_1 = a \doteq 0.77$

$b_o = \log k = 4.656 \implies k = 45,200$

Hence, $Y = 4.656 + 0.77X$, or

$$C(x) = 45,200\ x^{0.77}$$

This line of best fit may be plotted on the log-log graph of the cost data

@ $x = 1$ (thousand), $C(x) = 45,200$
@ $x = 10$ (thousand), $C(x) = 45,200(10)^{.77} = 266,000$

6.2 Optimal Design Period

It appears that the discount rate in Guatemala is in the range [10, 15].

From the cross plot shown in Figure 3.4 and using a = 0.77, the optimal design period (assuming no backlogs in demand) is as follows:

@ r = 10%, x* = 4.9 years
@ r = 15%, x* = 3.3 years

For other values of r, x* (the optimal design period) may be determined from the following equation

$$a = \frac{r\,x^*}{e^{rx^*}-1}$$

It is interesting to note that for the four Guatemalan towns in which the water demand study was commenced in 1968, the design period for water supply facilities was 25 years

6.3 Optimal Scale of Facilities

If x* is the optimal design period for facilities, then the optimal scale is x*D, where D is the (linear) growth rate in demand.

As shown above in 6.2, it appears that x* for water supply facilities in Guatemala is approximately four years

One of the objectives of the water demand study in Guatemala is to determine the growth rate in demand. Water demand and other data for a fairly typical town in Guatemala (Ciudad Vieja) are as follows:

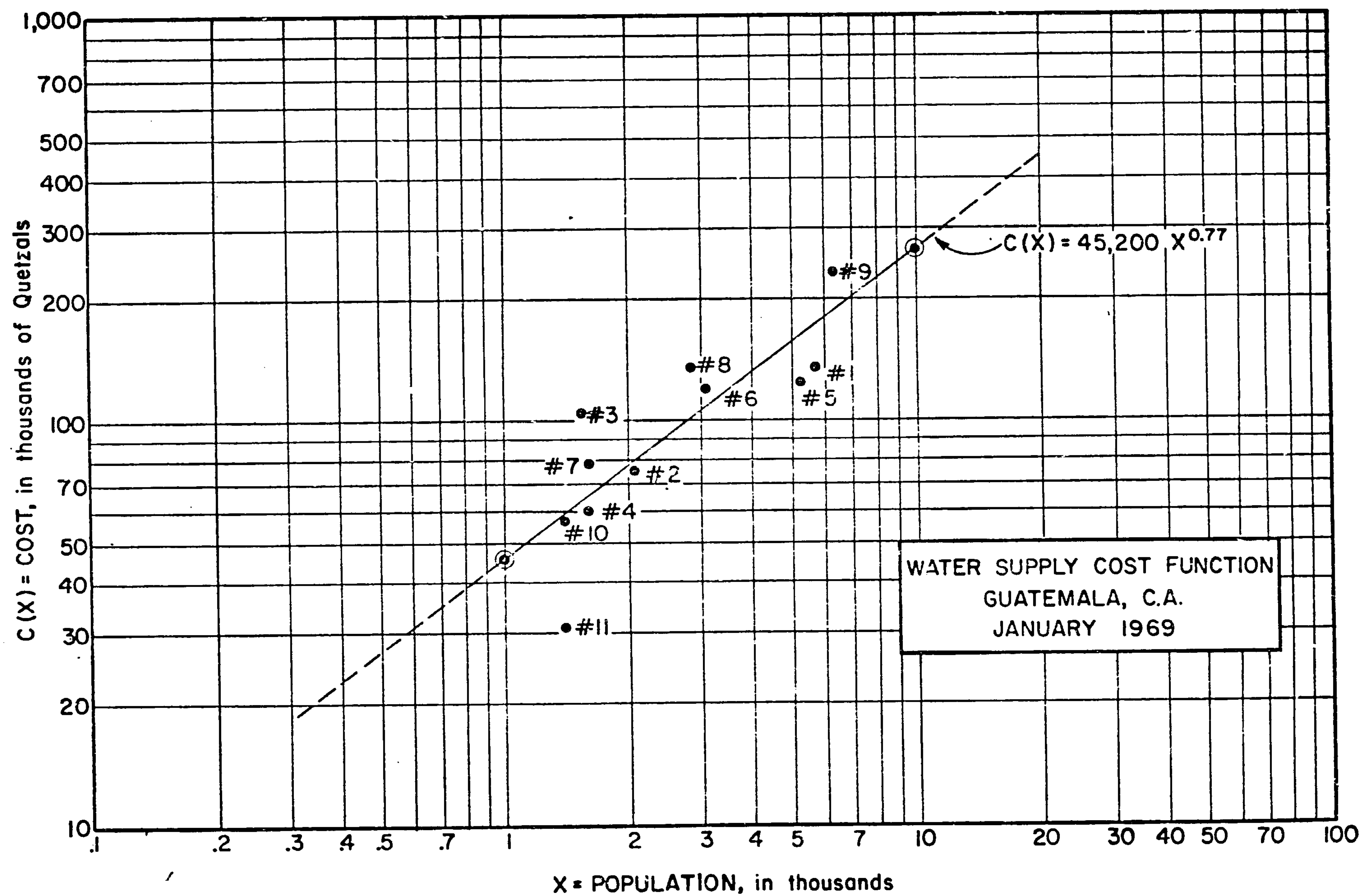
Name: Ciudad Vieja
Initiation of Public Water Supply Service: September, 1965

Year	1921	1950	1962	1964	1965		1966		1967		1968
Population	3610	4261	4955	5721							
No. Houses				995							
No. Water Connections					280		415		510		553(1)
Connection Growth Rate(2)						48		23		30	
Per Capita Consumption (3)					60		78		90		100
Consumption Growth Rate (4)						30		15		15	

(1) As of March, 1968
(2) percent per year; the overall average rate is 30% per year
(3) liters per capita per day
(4) percent per year; the overall average rate is 18% per year

Actual Design Basis

- The system was designed in 1962 when the town population was 4955.



C(X) = COST, in thousands of Quetzals
X = POPULATION, in thousands
C(X) = 45,200 X^0.77
WATER SUPPLY COST FUNCTION
GUATEMALA, C.A.
JANUARY 1969
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
1,000
700
500
400
300
200
100
70
50
40
30
20
10
.1
.2
.3
.4
.5
.7
1
2
3
4
5
7
10
20
30
40
50
70
100

FIGURE 6.1

- It was designed for a period of 25 years
- The estimated total population at the end of the design period (with population growth of 3/4% per year) was 5950.
- At 6 persons per house, the estimated total number of houses was 1000
- It was assumed that at the end of the design period only 70% of the houses would be connected (ie, 700 houses)
- The design flow (= average daily demand) was 7.17 liters per sec (= 150 lpcd with 4200 persons served)

Notes

1. In light of the above data and considering the short (4 year) optimal design period, it appears that a reasonable design basis might be the following:

   a) Assume 30% of the houses connect initially
   b) Therefore, new connections are made at the rate of 20% per year (over the design period)
   c) Assume initial per capita water consumption is 70 lpcd
   d) Thereafter, water use increases at the rate of 15% per year (as before)

2. Using this design basis, the optimal scale of facilities would be 5.3 liters per sec (300 houses x 6 cap/house x 70 lpcd $(1.25)^4(1.15)^4$ = 458,000 lpd = 5.3 lps)

3. A 5.3 lps system (w/a = 0.77) costs about 80% as much as a 7.2 lps system. Since the Ciudad Vieja system cost about Q 136,000, the smaller system would cost about Q 27,000 less.

4. If water supply planners in Guatemala consistently followed a (non-optimal) design period policy of 25 years instead of 4 years, in the long run, the excess costs in overdesign with a = 0.77 and r = 10% would be about 50 percent higher.

—//—

The p.v. expansion costs over an infinite time horizon are

$$C(xD) = k(xD)^a / 1-e^{-rx}$$

$$C(25D) = kD^{.77}(25)^{.77} / 1-e^{-.1(25)} = 13.1\ kD^{.77}$$

$$C(4D) = kD^{.77}(4)^{.77} / 1-e^{-.1(4)} = 8.8\ kD^{.77}$$

Hence $C(25D)/C(4D) = 13.1 / 8.8 \doteq 1.50$

7. SUMMARY AND RECOMMENDATIONS

Guatemalan water supply systems have largely been designed in the absence of data. Design standards based on thumb rules have been adopted, but these are suspected of being grossly inaccurate. Consequently, a water demand study was proposed in 1967 by the faculty of the Regional School of Sanitary Engineering at San Carlos University in Guatemala City. In 1968, a Task Order by the Community Water Supply Branch of AID authorized the International Program in Sanitary Engineering Design at the University of North Carolina to participate in this study.

Although the water demand study is immediately concerned with water usage, its long range concern is with the optimal sizing of water supply systems. Mathematical models by Manne and others have shown that the optimal scale depends not only on demand rates but also on the economies of scale associated with planning and construction. The economy of scale factor may be determined from least squares analysis of water system cost data. Determination of water demand factors may also be by linear regression methods, but this work is quite extensive and will only commence as the second stage of the Guatemala study nears completion. Such statistical analysis will largely comprise the third stage of the present study.

Preliminary results from Guatemala indicate relatively small economies of scale associated with water supplies which, together with high discount rates, imply short optimal design periods. Present design policy in Guatemala indicates that water supply costs are probably fifty percent above the optimal level.

In the second stage of the demand study which is just commencing, much attention should be paid to experimental design. Communities for study should be carefully selected so the parameters of a predictor model for water demand can be evaluated. Required metering equipment should be installed and initial evaluation and measurement work should be started. Continuous analysis of results should indicate those factors and characteristics which should be introduced or deleted from the study, and community study sites should be changed accordingly.

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APPENDIX A

GUATEMALA FIELD VISIT REPORTS - September, 1967

Report on

PROPOSED WATER DEMAND STUDY IN GUATEMALA

by

Donald T. Lauria

September, 1967

1. - INTRODUCTION

1.1 Study Proposal

Early in 1967, broad plans were made by the Regional School of Sanitary Engineering at San Carlos University for a community water demand study in Guatemala. The study proposal was stimulated by the lack of basic data for design of water supply systems. It was consequently feared that presently used design factors may be inaccurate and thereby result in systems which are not optimally sized. The general objective, therefore, of the proposed study is to obtain basic information on water use which will permit more accurate design of water supply systems.

1.2 U.S. Visit by Engr. Octavio Cordon

In order to assist with the proposed water demand study, staff members at San Carlos University recommended that Dr. F. Pierce Linaweaver, Jr., of Johns Hopkins University be retained as a consultant. In June, 1967, Engr. Octavio Cordon of San Carlos visited the United States, and his planned itinerary included a meeting with Dr. Linaweaver to discuss the proposed study. Engr. Cordon visited the University of North Carolina about two weeks before he was to meet with Dr. Linaweaver, and during this period it was learned that the group connected with UNC's International Program in Sanitary Engineering Design (and D. T. Lauria in particular) was interested in conducting a water demand study outside of the United States. At the time of Engr. Cordon's visit, the IPSED group had already contacted the Community Water Supply Branch of the U.S. Agency for International Development regarding a water demand study, and from discussions between Engrs. Cordon and Lauria it appeared that the proposed Guatemalan study would be a suitable project for both San Carlos and UNC.

As a result of discussions at UNC, it was agreed that both Engrs. Cordon and Lauria would visit Dr. Linaweaver in Washington to discuss the proposed study. A one-day meeting was arranged at which the general objectives of the study were discussed and plans were made for a visit to Guatemala at the end of the summer.

1.3 Preliminary Work

During the summer, preliminary work was done to summarize the findings of investigators who had performed water demand studies in the U.S. A literature study was made, and the results are included in Appendix A.

1.4 Formal Study Proposal by Regional School

In August, 1967, a formal proposal for the water demand study was prepared by Engrs. Cordon and Samayoa of the Regional School. Two broad objectives are described in this proposal: prediction of water demands in order to improve design of supply facilities, and development of a better understanding of the water demand phenomenon.

The document proposes that the study be carried out in three stages. In the first stage, two or three communities would be selected and basic data would be obtained on water usage. It is anticipated that experience to conduct future stages would be gained during this initial work, and one of the objectives at this point would be to demonstrate that a water demand study in Central America is practicable.

In approximately one year's time, the second stage would be started by expanding the study to include several communities. In this phase, data would be collected on a wider scale to further obtain fundamental information on the characteristics of water demand in Guatemala. In the third stage, more specific investigations and analyses would be made of water demand. The components of demand and its variation would be investigated, and relationships would be developed between demand and the factors which affect it.

In discussing the financial aspects of this study, the proposal notes that INFOM plans to purchase master meters for some fourteen or eighteen communities which might ultimately be included in the study. The long-range expectation of expanding the study to include other Central American countries is also mentioned.

2. - FIELD VISIT TO GUATEMALA

2.1 Objectives

During the period August 28 through September 11, 1967, Engr. Lauria was in Guatemala in connection with the proposed study. The broad objectives for this visit were to become familiar with conditions in the country and to work on developing more definite plans of action for the proposed study.

2.2 Meetings and Discussions

Several meetings and discussions were held during the visit. On August 29, Engrs. Cole, Cordon, Lauria, and Samayoa discussed the study proposal which had been prepared by the Regional School. Objectives were considered, and broad plans were described for the initial phases of work. On August 31, Engrs. Cordon, Lauria, and Samayoa met to discuss the kinds of data analysis which might be included in the work. A broad presentation of some of the analytical techniques which are described in Appendix A was presented, and time was spent in considering the nature of the factors upon which data would be collected in order to obtain correlation with water demand. In general, some of the more specific work which would be included in the third stage was discussed at this meeting.

On September 3, Dr. Linaweaver arrived in Guatemala, and the following day Engrs. Cole, Cordon, Gonzalez, Lauria, Linaweaver, and Samayoa held a general meeting to outline present thinking on the demand study. Much background information on Guatemala including the political subdivisions of the country and a description of various governmental agencies was presented. This meeting was continued in the office of Engr. Olivero, and in the afternoon, a general meeting was held in the INFOM offices with Engr. Fuentes and those who had participated in the morning sessions. At this afternoon meeting, some of the specific information on communities which had been proposed for study was examined, and arrangements were made to obtain additional data from INFOM.

On September 8, Engrs. Lauria and Linaweaver held informal discussions regarding the factors which should be investigated in the study, the methods that might be used to collect data, and the general work which would have to be done in the initial phases, and on September 9, Engrs. Cole, Cordon, Lauria, Linaweaver, and Samayoa had a general meeting to discuss the stages, organization, some of the already apparent problems, and prospective workers of the proposed study.

2.3 Field Trips

On September 5, field visits were made to Ciudad Vieja and San Antonio Aguas Calientes. Some time was spent in Ciudad Vieja inspecting the new pumping station and storage tank. The central pila in town was also visited as well as some private residences to inspect wells which apparently have not been used since piped water has been made available in town. The municipal building was also visited, and a brief inspection was made of meter and billing records.

On September 6, one of the pumping stations south of the Capitol which serves Guatemala City was inspected. A visit was then made to San Miguel Petapa where the intake, pumping station, and storage tank were visited. A general inspection was also made of this town. In the afternoon, San Lucas was visited. This community has a public sewage collection system, and it is somewhat different from other towns in that both old and new water distribution systems exist. In addition, water services are made off the main transmission line of the new system which runs from the source of supply to the distribution tanks.

September 9 was the first day of a two-day field trip. The trip was made through Escuintla and Mazatenango to San Francisco Zapotitlan where an inspection was made of the source of supply (which includes several springs) and the nearby system storage tank. This community, like San Lucas, is sewered. After leaving San Francisco the trip proceeded to Quezaltenango and Salcaja. On the way, a stop was made at San Luis where a new slow sand filter plant was being put into service. In Salcaja the source of supply, which includes an artesian well, was visited. This town is divided by a river, and there are essentially separate distribution systems including separate storage tanks on each side of the river. The housing characteristics of this community were significantly different from those of other towns visited. On September 10, the return trip to Guatemala City was made through Chichicastenango, Solala, and Panajachel.

2.4 Office Work

Much time was spent in reviewing data on the communities which have been proposed for inclusion in the water study. Based on a review and analysis of the data, tentative data collection sheets were prepared which include the factors which might be correlated with water usage (see Appendix B). Work was also performed with Engrs. Cordon and Linaweaver on establishing a basis for selection of master meters for the communities which would be studied.

2.5 Miscellaneous

On September 7 and 8, the Comite Consultivo Conference for the Regional School of Sanitary Engineering was held at San Carlos. On the evening of the 7th a reception was attended at the home of Engr. Cole for those who had attended the Conference together with representatives from ROCAP and the local AID Mission. On the evening of the 8th another reception was attended sponsored by the rector and administrators of San Carlos University.

3. - RESULTS AND CONCLUSIONS FROM TRIP

3.1 Community Characteristics

In general, the towns visited on the various field trips indicated that community characteristics are very heterogenous in Guatemala. Widely differing conditions were found in regard to water service, housing, utilities, and natural environment. Regarding water service, there is significant variation in the percentage of residences in the different towns which have individual connections to the water distribution systems. Also, some communities have many pilas and chorros while others have very few. In general, alternative sources of supply for those communities with piped systems are located at widely varying distances from the homes.

Housing conditions are quite different from one community to another as is population density. In some towns large cultivated plots of land are included on the residential sites while in others, cultivated plots are small or absent. The type of housing construction varys singificantly. In some communities, all properties are well fenced which makes delineation of individual properties possible, but in other towns properties are poorly fenced or not fenced at all. Some towns are basically agrarian and the residents are primarily self supported while in others, money income is received from outside work.

The presence of utilities is a variable. Some towns have many houses with electric power while in others, electricity is scarce. The existence of public sewage collection systems has already been noted as well as the presence of alternative water supply sources. Natural environmental conditions (topography, temperature, rainfall, etc.) also change radically from one area of the country to another.

The significance of the heterogeneous community characteristics is great. Because water systems must be designed for such different conditions, simple gross averages like per capita water use for towns of different size will probably be too general to be of widespread disign value. As a result, more specific factors may have to be developed, and the number of such factors will depend in part on the number of significant variable characteristics from one town to another.

The problem of defining measurable characteristics to relate with demand is also complicated by the variation in conditions. For example, the economic level of a water user probably affects the extent of water use. In some countries, personal income is a good measure of economic status, but it seems unsuitable in Guatemala since much of the population is self supported. As a result, some other measurable factor which applies to the existing mixed conditions must be found. A similar situation exists with lot size. Water use may be high where properties are large, and lot width or fence periphery might be a suitable factor to correlate with demand except for the fact that in some towns, many properties are unfenced or poorly defined which makes it necessary to find another parameter to represent lot size.

3.2 Data Availability

In general, it appears that much accurate data exists on community characteristics. For those towns where water systems have been constructed, maps are available. Very complete population data are also available which include distribution of the population by age, literacy, etc. Information on water facilities appears to be quite complete. Data on the number of house connections and the specific features of the water supply and distribution systems also exist. Much information has already been obtained on housing characteristics which among other things describes materials of construction. In addition to presently available data, local water system operators and other personnel who are familiar with the characteristics of their own communities are other potential sources of information.

As with community characteristics, useful information is already available on water usage. In general, house connections are metered, and therefore monthly water usage records are available for individual users. These records include water fees and usage which exceeds contract (paja) limits. While good information exists for individual users, essentially no data have been collected on total community water usage since master meters are not in use.

Unfortunately, little information is available which describes those conditions which change regularly. Little or no data are being collected on climatic conditions at the local level. Regarding water usage variation, no provision exists for daily measurements since master meters are lacking. Consequently, considering all available sources of data, it appears that a good situation exists for gross analysis of individual water use but not for total community usage or for variations in usage, either at the community or individual levels.

3.3 Equipment

As already mentioned, house meters are in use but master meters are not. In order to obtain data on total community water demands, arrangements would have to be made for installation of master metering equipment. In several of the communities it was apparent that difficulties would be encountered in properly selecting metering devices for this work. Anticipated flow variation is often such that propeller meters on supply lines from storage tanks would not be able to monitor the entire flow. In some cases where low demands are expected, the use of nutating disc meters is a possibility, but this type of equipment presents problems for measuring and recording flow variations. Some thought has been given to the use of propeller meters at points of water supply and level recorders on storage tanks which together would generally provide required information on total community usage. However, most water systems are manually operated and do not protect against storage tank overflow in which case level recorders would not properly indicate flows from storage tanks.

Aside from metering problems, serious equipment difficulties are not apparent. In the study, it will be necessary to select communities where demand is not limited by system deficiencies, and although there are some systems where quality of water service is inadequate, there appear to be a sufficient number of adequate systems to at least accomplish initial objectives of the study.

3.4 Personnel

In general, it appears that conditions for data collection are good. Sufficient personnel seem to be available to obtain initially required data and perform basic analyses. Sources of personnel to meet needs for the study should be able to include university students, governmental agencies such as the census department, public works, and health department, and local water works operators. Although data collection personnel seem to be available, at least for the initial stages, difficulties may be encountered in the future when the efforts of many workers will have to be coordinated and more intricate data analyses performed.

3.5 Financial

Serious financial problems are not anticipated for the initial phases of work. INFOM intends to provide equipment for master metering for the communities which will be included in the study, and this is a significant financial contribution. It appears that ROCAP will be able to support the engineers at San Carlos who will direct and coordinate the study, and ROCAP will also be able to help provide special consultants to assist University staff members. Looking one or more years into the future however, some problems might be encountered in obtaining satisfactory financial assistance. However, it is anticipated that aid may be obtained from international agencies such as US/AID or PAHO if initial work produces results which show significant promise for the study.

4. - GENERAL STUDY PLAN

4.1 Study Objectives

A general study plan has evolved which is fairly well defined for the initial phase and which recognizes some of the major problems which will be encountered in later stages. Some considerations of the general work of the study are included in this section.

The broad study objectives are those presented in the Regional School study proposal, viz.: prediction and understanding of water demands in Guatemala. In addition, several specific objectives can be defined: demonstration that a water demand study is practicable, development of gross average and peak per capita or per connection design factors, development of specific relationships between average and extreme water usage and measurable water user conditions and characteristics, and expansion of the study to include all of Central America.

4.2 Sources and Collection of Data

Many decisions will have to be made during the study regarding data sources. Four general questions which will have to be answered include the following: (1) what are the sources of water usage data, (2) what should be the characteristics of the data sources selected for the study, (3) how many data sources are required, (4) how long should the study be conducted. There are many other questions to be answered, but these are some of the most basic ones which will be briefly considered herein.

Two general types of water users exist: individual users (households, commercial establishments, schools, chorros, etc.) and communities. The basic water user in the community is the household, and much can be learned about water demand from individual meter records which are already available in fairly large quantities in Guatemala. However, water supply systems must be designed to meet total community needs, and since household records do not include commercial, unaccounted-for, public, and other use, they do not provide a complete basis for design although they do provide a basis for supplying the major component of total community demand. Also, much required information such as patterns of demand variation can most accurately and efficiently be determined from analysis of total community records. As a result, both individual and master meter data sources should be analyzed.

The required characteristics of data sources included in the study should be generally similar to the water users for which future supply systems will be designed in order for the study results to be of design value. However, in order to develop an understanding of the water demand phenomenon (which is the second study objective), a wide variety of user characteristics should be included in the work.

A consideration similar to the above is the need to evaluate the effects on water demand of certain community characteristics. Such evaluation will largely determine the suitability of specific data sources for future inclusion in the study. In general, the task is one of classifying water users according to their major characteristics which have a significant affect on water use patterns. Specifically, it will be necessary to learn whether the presence of public sewers affects water demand. If it is found that basically different amounts of water are used in communities (or by individual households) with sewers as compared to those without sewers, then it will be necessary to analyze sewered and non-sewered communities separately in the remaining work of the study, and it may be possible (or necessary) to eliminate one of these types of water users as a data source. A second characteristic which should be investigated is the proximity of alternative sources of supply. It is conceivable that in some communities with nearby alternative sources such as wells or rivers, water use patterns may be significantly different than in communities where alternative sources are very remote, and this must be considered in the data analysis.

The number of required data sources and the length of study is a function of the variation which is found in water demand from one user to another. In turn, the variation depends on two broad classifications of user characteristics and conditions, viz.: those which change with time and those which are essentially time independent. There are many social, economic, environmental and other conditions which vary among users and which affect water demand. At the beginning of the study, the number and exact nature of the factors which influence usage is not known, and consequently, some hypotheses must be made regarding these factors. For example, it might be assumed that water usage is affected by the existence of sewers and nearby alternative water sources, by economic status (e.g., type of house construction or electricity in the homes) and population density, etc. The minimum number of data sources must be sufficient to include different conditions for each of the factors assumed to affect demand in order to determine whether differences actually exist. By careful selection of users, several factors can be investigated simultaneously and the work of the study can be made much more efficient. Of course, if only the minimum number of data sources are included in the study, the degree of confidence in stating the effect of the assumed factors on demand will be low. Therefore, the number of data sources depends both on the number of factors and the required degree of confidence.

A situation similar to that described above exists for determining the length of study. Some factors (primarily climatic) which change with time affect demand. A sufficient length of time (probably only one year for climatic conditions) is needed to determine whether the time changes are significant, and thereafter, increasing the length of the study improves confidence in the results.

4.3 Data Analysis

It is anticipated that relatively simple analyses will be made of data in the initial stages of this study in order to provide as much usable information as possible for design purposes. Perhaps the most useful kind of analysis will be determination of average per capita or per connection usage within the various communities studied together with evaluation of demand variation (e.g., standard deviation). In this manner it may then be possible to obtain some kind of a relationship between average per capita use and one or more basic characteristics of the community such as size, density, etc. Initial data analysis might also include simple calculations of variation in usage in order to determine maximum-to-average daily ratios for different sized communities. Such relationships (that is, average usage versus different community characteristics, and peak-to-average ratio versus size) should immediately be of significant value in improving the design of new systems.

In the third phase of the study, more sophisticated data analysis can be made. Initial analyses in this stage might include multiple regression (both arithmetic and logarithmic) and might then possibly progress to some of the different types of time series analyses (see Appendix A).

4.4 Central America Study

The general study plan anticipates that the water demand study which will be started in Guatemala will be expanded to include the other countries of Central America. At the Comite Consultivo Meeting at San Carlos in September, it was agreed by representatives throughout Central America that work should be started outside Guatemala as soon as possible. As a result, it will be necessary for the work descriptions and findings of the Guatemalan study to be summarized at relatively frequent stages so that this information can be made available to the other countries where water demand studies will be started.

5. - RECOMMENDATIONS

5.1 Equipment

One of the first tasks of the study will be to select master metering equipment for several water systems throughout the country. The master meters should be capable of measuring total flows, flow variation, and of being equipped with recorders. Propeller meters on tank outlets are probably the most economical units which generally meet requirements but they unfortunately cannot be applied to all systems. Nutating disc meters should probably be used where flows are low, but they will require manual reading (sometimes continuously throughout the day) at certain times during the study. Where propeller and disc meters are unsuitable, it might be possible to meter the source of supply with propeller meters and install level recorders on storage tanks. If level recorders are used, it will be necessary to make some provision to prevent storage tank overflow to make level data useful. This can be done through manually controlling the supply source if the system operator is sufficiently aware of the problem.

However, in order to provide more positive protection against tank overflow, it might be desirable to install float valves on inlet lines or provide float switches for pumped supplies where this can be done economically.

Although permanent master meters are desirable for purposes beyond the scope of this study, care should be taken to ensure that proper equipment is selected to provide the information required by this study as well as satisfy objectives extraneous to the study. In this regard, it is recommended that both homemade and commercial pitometers be evaluated for metering use in the study.

5.2 Data Collection and Analysis

It is anticipated that several months will be required to obtain and install master metering equipment. Consequently, it is recommended that work not be delayed until metering installations are completed but that use be made of individual records which are presently available. Household water use should be analyzed in two or more communities to evaluate the effect of sewers and alternative sources on demand so that proper plans can be made for selection of communities when metering installations have been made. Other factors such as population density, economic status, rainfall, etc. might also be investigated on a preliminary basis through analysis of individual records. In general, to investigate any of the factors suspected to have correlation with water demand, it will probably be desirable to select users of approximately uniform characteristics except for the factor being investigated so that interference from other variables can be minimized. As originally planned, work might start in Ciudad Vieja and Petapa.

In addition to collection and analysis of individual records, it is recommended that arrangements be made to start collecting and tabulating data on the characteristics of some of the communities which might be included in the study. Data tabulation sheets should be developed. Those in Appendix B might be used as a guide.

Regarding all aspects of data collection and analyses in the first stage, it is recommended that time schedules be established so that proper plans and arrangements for study continuation can be made.

5.3 Personnel

Work should be started to incorporate personnel from governmental and other agencies in the water demand study. Students from San Carlos University might be used for preliminary analysis of individual records. The cooperation of local water works personnel might be sought so that they will be properly prepared to serve the project when more active participation is required. In addition, full use should be made of consultants in the early stages to ensure that proper arrangements are made for data collection and analysis.

5.5 Financial

It is recommended that an objective be established for obtaining basic information on per capita water use in communities of various size within approximately one year so that these results can be used with international and other organizations for obtaining financial aid for the remainder of the study. Since arrangements for financing will probably take several months, it will be necessary to seek such aid some time before existing funds are exhausted. As a result, reasonable but fairly firm time schedules should be established so that data and results will be available when required.

APPENDIX A

WATER DEMAND

A demand function is a mathematical or graphical expression which relates the quantity of goods demanded in a sales market with those measurable market conditions upon which demand depends. Since many different factors account for demand, multivariate functions are likely to be most accurate, but it is much more common to find univariate functions used to represent the demand phenomenon which include only a single causal variable. One of the most important demand functions is the one used so extensively in economic theory (4, 13) which relates quantity demanded and price. This general function has been greatly studied and interpreted, and it is the prototype for many empirical demand models.

Demand functions perform several different tasks. Most basically, they indicate those factors which are related to the demand for goods and the effect which each factor has on the quantity demanded (e.g., price elasticity of demand). In applied work involving economic problems (i.e., where resources are scarce), demand functions are essential to decision making; they both indicate the magnitude of the quantity demanded, and, where price truly represents consumer willingness-to-pay, they provide a measure in money units of benefits from consumption (4, 13, 14, 22). Consequently, it is most important that demand functions be evaluated in order to provide for economically optimal use of resources.

Much work has been done in nearly every field of marketing to determine empirical demand functions. Indeed, the discipline of econometrics which includes the statistical techniques required to evaluate demand from market surveys has been developed partly for this purpose (27, 29). Part of the reason why econometrics qualifies as a specialized branch of statistical analysis is that it makes use of analytical procedures which are needed to cope with the central problem of demand analysis; viz, the non-experimental nature of market statistics.

Econometrics is a relatively young and rapidly growing discipline. Prior to development of modern econometric techniques, studies to empirically determine demand functions were usually very simplistic, and results were often unconvincing and of questionable value. Indeed, simple analyses generally characterize the work which has been done to determine the demand for water. However, within the past ten years, some water demand studies have used more sophisticated methods of analysis, and the purpose of this paper in part is to examine some of the water demand studies which have used both the older, more conventional methods of analysis, but primarily those which incorporate modern econometric techniques.

The multitude of considerations which are related to water demand are vast and consequently cannot all be included in this paper. However, many of these considerations will be touched on herein. Specifically, this paper will cover the following:

1. A brief discussion of some of the factors and events which make up what might be called the phenomenon of water demand, and
2. Some of the objectives, methods, and results of completed water demand studies which have been performed in the United States.

1. THE PHENOMENON OF WATER DEMAND

1.1 Water Users

The basic element in all demand situations is the individual consumer, and many demand studies in the water supply field have concentrated solely on the individual. The aggregate of individual demand constitutes market demand, and in the case of water supply, the market most often studied is the total community. In general, most water demand studies have been performed in urban areas where a large variety of individual consumers exist, and it is such studies which are primarily considered herein.

Water is used in municipalities by many types of individual customers and for different purposes. One classification which can be made of water users is the following: domestic, commerical, industrial, public, and other (16, 20, 24). The corresponding classification of water use is for domestic, commerical, industrial, public and miscellaneous (or unaccounted-for) purposes. Domestic customers consume water for household use which also includes lawn sprinkling, car washing, home swimming pools, etc. The primary use of commerical and industrial water is for production purposes which include process water, cooling water, water for washing and cleaning, and waste transport. It is often difficult to clearly distinguish between commerical and industrial use, and usually, some kind of arbitrary distinction is made. Public use includes water for street washing, fountains, parks, public swimming pools, fire protection, etc. Unaccounted-for water is usually denoted as the difference between water production (at the supply or treatment facilities) and water sales (which, of course, are only known in a completely metered system). Under this definition, unaccounted-for water usually includes most of the water used for public purposes.

1.2 Patterns of Water Use

Water usage in a community varies considerably with time. Although it is possible to arbitrarily subdivide time for the purpose of examining patterns, and trends of water use, it appears that the most common subdivisions are the following: daily, seasonal, and annual (10, 23, 26, 30).

Water usage may vary greatly throughout the day at both individual consumer and total community levels. Highest normal demands for individual domestic users and

and communities which are primarily residential are usually encountered in the morning when families are starting the day. Demand usually declines after this until late afternoon when workers return home at which time a second, smaller peak occurs. Where large sprinkling demands exist, peak periods are often in late afternoon. Minimum demand is encountered around daybreak or slightly before (5, 26, 31).

Daily demands may fluctuate widely from one season to another. In general, maximum daily demands are encountered in hot summer months when bathing is more frequent, lawns are being watered, water is used for outdoor washing and swimming pools, and air conditioning demands exist. Correspondingly, minimum daily demands occur in cold winter months (10, 26).

Annual trends of community water use usually exist (19, 24, 26). These trends are primarily due to changes in the number of water users (domestic, commercial, and industrial). Even where numbers of users do not substantially change, trends may exist because of changes in water-using habits and numbers of water-using appliances.

1.3 Factors Which Are Related to Water Usage

An exhaustive list of market conditions and factors which are related to water demand will probably never be available. However, some factors which have been found to be significant (or thought to be so) can be cited. As conditions vary from one community to another, the magnitude of effect which the factors have on demand may change greatly, and new factors may be related to demand in some towns which are insignificant in others.

Before listing the factors, two points will be mentioned: first, these factors cannot definitely be said to "affect" demand in the sense that they are "causitive" factors (18, 27, 29). Indeed, this problem of causality is just another facet of the previously mentioned non-experimental nature of demand analysis which creates so many difficulties in demand studies. When regression or other analysis is used to determine demand interrelationships, the mathematical analysis generally does not permit it to be said with certainty that the related factors actually are the cause of demand. Causality is often implied and it is knowledge of causitive factors which is desired by the analyst, but care is needed to make proper interpretation of analytical results.

The second point is the role which these factors play in demand analysis. As we shall see, the demand function is empirically developed from a hypothetical mathematical model which includes those factors which are assumed by the investigator to have a significant relationship with demand (27, 29). Consequently, the accuracy and usefulness of the demand function depends to great extent on whether the investigator incorporated the correct factors in his model, and therefore, an understanding of the factors which relate to demand is essential to successful demand analysis. In connection with this point, it should be noted that empirical demand functions only include measurable factors, but it is quite probable that other factors and conditions exist in water markets which are related to demand but which are not included in demand models because they cannot be satisfactorily expressed in quantifiable units.

It appears that all of the factors which are related to the community demand for water can be classified into six categories: social conditions in the community, economic conditions, natural environmental conditions, quality of water service, quality of the water supplied, and cost of water. This classification indicates that the first three categories of factors are related to conditions in the community, and the last three are related to the water product which is offered for sale.

Social Conditions

In considering social conditions which relate to water usage, it is necessary to distinguish between individual and market demand. In the case where the "individual" is a family unit (e.g., a single water service), some quantifiable factors include the number and age of persons in the household; the number of water taps, toilets, and other water using appliances in the home; the existence of a sewer connection or septic tank; and the size of houselots. For total community demand, the factors include total population; area of the community; total number of houses, commercial establishments, and industries; the number of employees and self-employed members of the community; the total length of sewers; the number of public and private sewer connections; the age distribution of persons in the community; and the number of public swimming pools, parks, fountains and other facilities.

Although the above lists are not exhaustive, they do include factors upon which quantifiable data may be obtained, and consequently, these factors may be incorporated in mathematical models which are used to investigate and describe water demand phenomena. The same is generally true of factors in the other categories which are considered in this section.

Economic Conditions

It seems reasonable to expect that the level of economic prosperity in a community or with an individual consumer unit is related to water demand. One's ability to pay for water and afford water using appliances should be a basic element of the demand phenomenon. The following economic factors may therefore be related to total community water demand. As with the case of social factors, many of the items listed below could be related to individual household demand merely by changing the units of measurement (e.g., individual personal income instead of total community personal income). Some of the factors are: personal, commercial, and industrial income; the number of automobiles in the community; number, size and type of construction of buildings; personal, commercial, and industrial income taxes; the valuation of properties; and the number of privately-owned properties. In the case of water demand in developing countries, the factors might also include the number and kinds of beasts of burden; the availability and cost of electricity; church income; the length of paved streets; and similar items which reflect the economic well-being of the community.

Natural Environmental Conditions

Natural environmental conditions often have a significant relationship with water demand; it has already been voted that peak residential demands occur in hot, dry summer months. Natural environmental conditions primarily include factors which relate to the weather, although in some cases, geological and topographical conditions might also be significant. The primary factors are: temperature—e.g.: mean, noontime, nighttime; rainfall--e.g.: mean, frequency (number of days per month), number of consecutive days, duration and intensity, etc.; distribution of sunlight; elevation of the community above sea level, and differences in elevation. Such things as soil conditions, elevation of the ground water table and proximity to alternative sources of supply may also have bearing on water demands.

Quality of Service

Distribution pressures, leakage through joints, the volume of system storage and interruptions in supply service all relate to demand. Other factors which generally indicate the quality of water service include the length of pipe in the distribution system, the number of valves, the number and size of connections, the age of the system, type of supply (e.g.: gravity, pumped), and the number of meters. This last factor (meters) has often been singled out for use in demand models since it may be an important parameter (like sewers) which has basic affect on water demand patterns (20, 24). Other factors which may correlate with demand include the number of system operators, and in the case of developing countries, the number and type of public fountains and public washing stations.

Quality of Water

Intuitively, water quality seems to be related to demand. It seems natural to expect high demands when water quality is good. Little work has been done on investigating the effect of water quality on demand. In much of the U.S., water quality is generally good, and large enough differences in quality do not exist so that measurable effects results. Also, water quality is a relative thing; what may be unacceptable in one community if encountered for short periods of time (e.g., tastes and odors during short periods in the summer) may be generally accepted in another if the condition is more or less constant (other examples include high turbidity, iron and manganese, and hardness concentrations). A quality factor which has been noted to have some relationship with quantity demanded is temperature.

Cost of Water

The price of water is a factor which bears on the quantity of water demanded, and many studies have been performed to investigate price effects (9, 15, 19, 22, 33). In the U.S. it has generally been found that price changes do not greatly affect quantity demanded (i.e., demand is highly inelastic). Consequently, price is usually not a significant factor in affecting water usage in the U.S. However, such is generally not the case in the developing countries of the world.

In addition to the price of water, excess usage charges, system operating costs and capital costs all relate to water demand.

2. WATER DEMAND ANALYSES

2.1 Objectives of Demand Analysis

Demand studies are usually performed for two purposes: (1) prediction of future demands, and (2) definition of structural relationships between the commodity demanded and the factors which relate to demand (27, 29). This last objective is generally set in order to obtain a more complete understanding of the theory of demand.

As a practical matter, probably more water demand studies are undertaken to achieve the first objective than the second. Such studies include the work of planners and engineers who are faced with the problem of predicting demand in order to design water supply and distribution systems.

The bulk of water demand work in the literature describes development of interrelationships between water demand and factors similar to those mentioned in section 1.3. The interrelationships are used for both prediction and theoretical purposes. For prediction purposes, water usage is usually correlated with factors which can be readily measured, and determination of the mathematical function which defines the interrelationship is the desired objective of the study. For theoretical purposes, the investigator is often not so interested in a precise mathematical expression as in knowing which factors have a statistically significant relationship with water usage and the relative importance of each of those factors (18, 29, 33).

From the foregoing, it should be apparent that the objective of defining structural relationships (and thereby substantiating theoretical hypotheses) is a difficult one to achieve. The theoretician generally seeks those factors which cause demand, but because the data he works with are non-experimental, it is difficult to know if the statistical interrelationships found actually define the essence of the demand phenomenon (18, 33).

Contrasted with the difficulties of confirming theoretical hypothesis through empirical demand studies, it is generally safe to use the results of statistical demand analysis for prediction (29). Here, the mathematical expressions define valid interrelations upon which statistical confidence limits can be imposed. No attempt is made to define cause and effect, and as a result, within the statistical accuracy of the analysis, the functions may be used for prediction.

2.2 Water Demand Studies

It is difficult to classify the many different kinds of water demand studies which have been performed. However, a very broad division can be made according to the primary objective of the study; viz, for prediction purposes or theoretical purposes.

Prediction studies often include some type of time series analysis to determine trends of past use. A historical record of demand data is analyzed and the results are projected into the future. Such studies have been performed for many different kinds of water users and markets (2, 3, 7, 8, 9, 26, 30). Probably the most common is analysis of total community demand since this represents the market for which water supply facilities are most often designed. Either total daily demand or total annual demand is projected.

Prediction analyses are also made for the components of total community demand; i.e., for individual demand. Analysis of domestic consumption (either per capita or per connection) is common, as is analysis of specific industrial and commercial usage (1, 5, 9, 11, 14, 16, 19, 20, 30). Large components of total community usage have been broken down into subgroups for analysis. Specific apartment house (5) and individual homeowner studies have been made.

Other types of demand studies which generally fall within the prediction category are analysis of extreme demands (12, 23, 31) and demand variation (2, 10).

Much work has been done to analyze peak demands since this information is needed for design of system storage requirements. In the 1940's and early 1950's, fire and air conditioning demand studies were common. In more recent years lawn sprinkling studies have been performed (12, 15). Regarding demand variation, some work has been done to analyze daily, weekly, monthly, seasonal and annual variations in community and industrial demands.

A variety of studies for theoretical purposes have been performed (9, 14, 15, 17, 20, 24, 25, 33). Water demand data have been analyzed to determine relationships between usage and all of the factors mentioned in section 1.3. Simple univariate regression analyses have been most common, but a few studies have been made to determine relationships between consumption and several factors.

2.3 Data Collection

It has been most common in the U.S. to use historical records of available data for demand analysis rather than include field data collection as part of the demand study. As a result, most studies are of a somewhat general nature. Several studies have been performed using data collected from national surveys (20, 24, 25), but most have included recorded data from separate municipal or larger regional areas. In the case of a few special studies, it has been necessary to collect data to obtain proper information on the particular factors incorporated in the demand models (5, 15).

2.4 Data Analysis & Results

As noted in the introduction to this paper, many types of data analysis have been used in water demand studies, ranging from very simplistic procedures to the most modern mathematical techniques. For purposes of discussion, the methods of data analysis are classified as follows: comparative, graphical, univariate regression, multivariate, and time series.

Comparative

Many water demand study reports merely present comparative tabulations of data. Porges (20) presents average daily per capita usage data in a two-way table comparing municipal size (by population) and percent of the municipality which is metered. He also tabulates average per capita consumption by geographical locations. Similar tabulations to imply climatic and other effects on water demand are common (2, 14, 24, 25).

Graphical

Graphical methods are used for both data presentation and data analysis. Field data or calculated results are often presented in bar charts for comparative purposes. Plotted time series are sometimes used to show variations in demand. Probably the only kind of true graphical analysis is simple regression fit by eye.

Seidel (24, 25) uses bar charts extensively to compare water production, sales, etc. for different size municipalities. Means, medians and quartiles are indicated on the bar charts. Porges (20) uses bar charts to compare per capita consumption among different geographical locations and also for different levels of precipitation. Similar uses are made of bar charts when only two factors are compared.

Historical records are often plotted to show variations in water demand (2, 10, 19). Gracie (10) shows both daily and weekly variations graphically. He also presents the results of time series analysis in graphical form.

Simple univariate correlation performed graphically rather than algebraically is very common in water demand analysis. Metcalf (19) in an early (1926) paper on water demand analysis made several data fittings graphically. (One of the fittings was to determine the effect of price on water sales which is one of the earlier works which includes price as a factor). In addition, most prediction analyses are of the graphical type.

Univariate Regression

Simple linear regression (performed by least squares) is the most common method of data analysis in water demand studies. Univariate regression is used to regress a dependent variable against a single independent variable. A theoretically linear demand function of the following form is postulated: $Y = AX + B$. According to this hypothesis, changes in the independent variable X produce changes in the dependent variable Y, where Y is "quantity demanded". (Independence and dependence imply cause and effect.) By the method of least squares, an empirical relationship $y = ax + b$ is calculated which estimates the hypothetical demand function. In the case of logarithmically linear univariate demand functions, the model is: $Y = BX^A$.

Water demand literature abounds with linear relationships between water usage and a single factor (e.g., price (9, 19, 22), economic activity (7), personal income (16), and time (2, 11). Gottlieb (9) determined logarithmic univariate relationships using price and personal income.

Multivariate Analysis

Multiple linear and logarithmic demand functions which include several independent variables have the forms: $Y = B + A_1X_1 + \ldots + A_nX_n$, and $Y = BX_1^{A_1} \cdot \ldots \cdot X_n^{A_n}$, respectively. Fourt (8) performed multiple linear regressions to find relationships between water usage and price, number of days of summer rainfall, average number of persons per meter, and total population served. Howe and Linaweaver (15) worked with logarithmic demand models incorporating several independent variables for both average domestic demand and sprinkling demand.

More sophisticated multivariate techniques are coming into use in water demand analysis. Wong et al. (35) have used the methods of principal components to analyze domestic demands in Illinois. Although not yet used in the water supply field, it is probable that factor analysis (18, 27) and other multivariate techniques will also find application in demand analysis.

The underlying objectives of principal components and factor analysis are to: (a) analyze a large set of correlated variables into a smaller set of independent variables (called "principal components" or "factors"), and (b) determine the portion of total variation in the dependent variable which can be accounted for by each of the factors.

In the work reported by Wong (33), an initial set of twenty variables incorporated in the water demand analysis was reduced to a set of seven principal components which accounted for over 86 percent of the total variation of the original twenty variables. The most significant of the factors was the structure of housing in the communities studied. Other important factors were: community size, per capita demand, price, standard of living and industrial complexion.

Time Series Analysis

Time series analysis includes statistical methods which can be used to analyze phenomena which occur as a succession of events in time. In such phenomena, the events are not random (i.e., not independent). Rather, some dependence among events exists, and the statistical methods of time series analysis attempt to cope with this problem of time dependence of data.

In general, the methods of time series analysis are based on the hypothesis that (a) there is a "true" underlying pattern of time change in events, with random fluctuations superimposed, or (b) the time series is autocorrelated; i.e., the events in the series are correlated with other events in the same series separated by a certain lag, and errors of observation may exist. Harmonic (or Fourier) analysis generally includes the statistical procedures which are based on the first hypothesis, and autocorrelation techniques are based on the second (27).

Tintner (27) notes that harmonic analysis is based on "the idea of the independence of the various components of a time series, trend, cycle, etc. These assumptions

are hardly tenable, and the methods cannot give us more than very rough approximations".
The basic model of harmonic analysis is:

$$Y_t = \bar{Y} + \sum_{k=1}^{T/2} (A_k \cos wtk + B_k \sin wtk),$$

which is equivalent to:

$$Y_t = \bar{Y} + \sum_{k=1}^{T/2} (C_k \sin (wtk + D_k))$$

Y_t is the observation at time t and $\bar{Y}$ is the mean observation of the entire series. It can be seen that the model assumes Y_t is a function of a deterministic element $\bar{Y}$ and a collection (in this case, a sum) of random elements. Each of the random elements in the collection is a sine curve and is called a harmonic. k is the harmonic number, and the greatest number of harmonics required to completely describe the process is T/2, where T is the total number of equally spaced observations in the series. A_k and B_k are constants associated with the k-th harmonic. C_k and D_k are the amplitude and phase angle respectively of the k-th harmonic, and each of these factors is a function only of A_k and B_k. Harmonic analysis, then, consists of determining the constants A_k and B_k (or correspondingly, C_k and D_k) for a given time series. Once the factors are evaluated, the model is completely described and Y_t for any t may be calculated (i.e., prediction of any future Y_t is possible).

Autocorrelation analysis (27, 34) is made in order to identify dependence in a single trace of data. The analysis consists of developing autocorrelation and spectral density functions from the original data record. These functions provide information on data correlation in the time and frequency domains, respectively. The spectral density function is developed from the autocorrelation function, and it provides no new information. However, it presents analytical results in a different and possibly more useful form.

The dependence of observation in a data trace separated by a lag of p time units can be identified by the autocorrelation coefficient r_p which relates them. The mathematical expression is:

$$r_p = \frac{\sum Z_t \cdot Z_{t+p}}{\sum Z_t^2}, \quad t = 1, \ldots, N-p$$

where Z_t is the normalized form of Y_t and N is the number of points in the series. The coefficient r_p assumes values between +1 and -1. High positive values indicate positive correlation, and vice versa; an autocorrelation coefficient of zero indicates that the observations are uncorrelated (which implies independence). In the case of water demand, r_p values which have relatively high positive value indicate that high (low) demand one day will be followed by (or lead to) high (low) demand p days later. It should be apparent that r_p calculated for zero lag has a value of +1.0. It might also be apparent that as p increases, r_p usually approaches zero since it is not highly likely that events separated by a long lag period are strongly correlated. As a practical matter, the number of lag periods for which coefficients are calculated is usually about ten percent of the time periods in the data trace (i.e., for a one-year trace of 365 observations, the number or r_p values calculated would be about 36).

After r_p is calculated for several values of p, the results can best be presented in a graph of r_p versus p. This is called a correlogram and it shows the time lags for which significant autocorrelation exists.

The spectral density U_p of a data trace can be determined from analysis of autocorrelation coefficients (34). Autocorrelation is a function of autocovariance W_p, and sample variance: $r_p = W_p/s^2$. Hence, autocovariance factors can be easily calculated. If a Fourier transformation (i.e., harmonic analysis) is applied to the autocovariance factors and these factors are then smoothed by the method of moving averages, U_p values result. Final data presentation is best made graphically in a plot of U_p versus frequency.

Gracie (10) has made extensive analysis of average daily water demand data for 1962 and 1963 for Champaign-Urbana, Illinois, the Belmont high-service district in Philadelphia, and Denver, Colorado. One of the objectives of his study was to determine whether variations in demand could be adequately represented by deterministic models such as harmonic functions and spectral density functions. Simple graphical analyses and analysis of variance showed significant variation in average daily demand by days of the week and weeks of the year for Champaign and Denver. Variation by day-of-the-week was not significant for Belmont but weekly variation was significant.

Having obtained these preliminary results, harmonic analysis was performed to determine periodicies in the data. High values of C_k (the amplitude of the k th harmonic) were found for the first, 52nd, 104th and 156th harmonics in the case of Champaign which clearly indicated a weekly cycle in the demand phenomenon. Little interpretation could be made of the Belmont results since there was no regular pattern in amplitude variation. However, the Denver results also indicated a weekly cycle in demand, but in addition, a weak biweekly-period was also evident.

Autocorrelation analysis strongly confirmed the weekly cycle of demand at Champaign since high autocorrelation cofficients were found for seven-day lag periods (and multiples thereof.) However, results were inconclusive for Belmont, and the only significance of the Denver data was the close similarity of the 1962 and 1963 results, but strong periodicies were absent. As might be expected, the spectral density function for Champaign again indicated a weekly cycle in demand but satisfactory interpretation could not be made for the other areas except that low frequency harmonics were the principal sources of variation in daily demands for all communities.

3. SUMMARY

A water demand function is an expression which relates quantity of water demanded to one or several variables in the water market. Such functions may be developed for different size water markets, but community functions are most common and generally of most applied value since water supply facilities are usually designed on a community basis. Demand functions may be developed for average or extreme rates of usage.

Empirical water demand studies are usually made either to predict future water usage or to improve understanding of the water demand phenomenon. In empirical studies, the investigator postulates a model which includes (a) the different factors which are assumed to be related to quantity demanded and (b) the kind of interrelationship among factors and the dependent variable which accounts for water demand. The factors included in the model are quantifiable ones which may be generally classified into six categories: social, economic, and environmental conditions in the market, quality of water service, quality of water supplied, and cost of water.

Univariate linear models are the most common forms which have been used to express water demand. Within recent years multivariate models have come into greater usage, and these are generally of the linear or logarithmically linear types. In a recent study, the method of principal components was used to reduce a large set of factors to a smaller set of uncorrelated variables, and it is probable that other multivariate techniques will soon find application in the water demand field.

A study reported in 1966 made use of harmonic and spectral density analysis to investigate time variations in average daily water demands in three U.S. cities. The results of these analyses were difficult to interpret and for two of the cities, they provided little information beyond simple algebraic analysis and analysis of variance. However, time series analysis attempts to more accurately describe the demand phenomenon (as a deterministic process) and like multivariate analysis, it will probably be more extensively used in future water demand work.

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APPENDIX B

Water Demand Study

Community Characteristics

Date________________

Engineer________________

1. Community Name______________________________________

2. Population: 1964 Census____________________, Present Estimate______________

3. Total Families (Houses) in Town______________

4. No. House Connections (Meters) to Water System______________

5. No. Chorros_______________

6. No. Pozos: Public______________, Private________________

7. No. Pilas____________, Total No. Stations at Pilas________

8. No. Houses with Water Meters and Public Sewers______________

9. No. Houses with Water Meters and Latrines__________________

10. No. Houses with Water Meters and Electric Power______________

11. No. Houses with Public Sewers_____________

12. No. Houses with Latrines_____________

13. No. Houses with Electric Power_____________

14. Estimated pressures in distribution system:

    Minimum____________psi; Average___________psi; Maximum_________psi

15. Alternative sources of supply (describe):

16. Piping Characteristics: Length ≤ 1"_______ft, 1 1/4 - 1 1/2"_________ft,

    2"_____ft, >2≤3"_________ft, >3≤4"__________ft, >4≤6_________ft,

    >6"________ft.

17. No. Houses with Water Meters in which Principal Worker is Farmer for himself

    ____________________, for someone else_______________

18. No. Houses in which Principal Worker is Farmer for himself______________,

    for someone else________________

Water Demand Study (cont'd)

19. Excess Monthly Service Charge:________________ per__________________

20. First Month Water Service Available________________________, 19_______

21. Remarks:

Water Demand Study

Monthly Community Data

Date ______________________

Engineer ______________________

Community Name ______________________

Data for Month of ______________________, 19______

Day	Water Usage (m^3)	Noon Temp (°C)	Rain (Yes/No)	Duration without Water Service (hr.)	Remarks
1					
2					
3					
.					
.					
.					
31					

1. Church Income ______________________
2. Total Excess Service Charge Paid this Month ______________________
3. No. Customers who paid Excess Service Charge ______________________
4. Total Monthly Water Usage ______________________ m^3
5. Average Daily Water Demand ______________________ m^3
6. Maximum Daily Water Demand ______________________ m^3
7. Minimum Daily Water Demand ______________________ m^3
8. Average Noon Temperature ______________________ °C
9. No. Days of Rain ______________________
10. Average No. Hours without Service ______________________
11. Total No. Hours without Service ______________________
12. No. Months Since Water Service First Available ______

Report on Visit to the University of San Carlos on Water Demand Study
September 3-13, 1967

by F. Pierce Linaweaver, Jr.

The purpose of the visit was to advise the Regional School of Sanitary Engineering on their proposed study of water demands in Guatemala. It has been planned that the study would be expanded to other Central American countries during the second stage of the study. This received a considerable step forward on September 8, 1967 when the Consulting Committee of the Regional School of Sanitary Engineering with representatives from Guatemala, San Salvador, Honduras, Nicaragua, and Costa Rica passed a resolution approving the study and calling for its expansion to the other Central American countries within the year.

At an earlier meeting in Washington, D. C., on June 29, 1967, Engineer Octavio Cordon of the Regional School discussed the proposed study and invited me to participate as a consultant to guide them in setting up the project. Prior to my visit to Guatemala, Engineer Cordon and Engineer Otoniel Samayoa, also of the Regional School, prepared a statement on the study objectives and the proposed work plans which can serve as an excellent overall guide for the study. The primary objective is to improve estimates of water demands and their variability in order to insure the proper design of water distribution systems. The extent of the program should be sufficient to develop general estimates of water demands and their variability that will be reliable for proper design within acceptable limits.

The study is planned in three stages. In the first stage, two or three communities in Guatemala would be selected for study to determine actual water use, to gain experience in the appropriate metering equipment for measuring water use, and to set up a procedure for the collection and analysis of the data. In the second stage, the number of communities under study in Guatemala would be expanded to the full program there and the water use study would be expanded to other Central American countries. In the third stage, the collection of data would be expanded to include detailed information on land use, socio-economic factors such as family size, environmental conditions such as the weather, pricing of water, and other factors in order to investigate the degree to which the various factors influence water use and to develop a design criteria which can readily account for the different characteristics between communities.

The principal immediate difficulties to start the first stage are to determine data requirements, to select the study areas and the water metering equipment, and to set up a procedure for the initial processing of water use data. Engineer Cordone listed eighteen communities which could be considered for inclusion in the study. These are shown in Table 1. All 18 communities have recently built public water supplies through the investment programs of the Institute de Fomenta Municipal (INFOM). All services connected to the systemshave individual water meters. The systems generally lend themselves readily to the installation of master metering equipment.

During my visit, field trips were made to five of the communities listed in Table 1, in order to understand local conditions, and to determine the water use data needed and how they should be obtained. The communities visited included San Francisco Zapotitlan, Ciudad Vieja, San Miguel Petapa, Salcajá, and San Lucas Sac. These communities provided a cross-section of various local conditions and included systems having different types of facilities. Some are supplied by gravity and others by pumped supplies with the pump and storage tank connected to the distribution system in various ways.

The selection of the water use study areas for the initial stages of the study from among communities under INFOM's program suggests that the initial results will be representative of primarily the smaller urban communities. Guatemala has a total population of about 4,500,000 people. INFOM's program is directed toward the approximately 800,000 people in Guatemala who live in urban communities under 25,000 persons in size. The two larger cities, Guatemala and Quetzaltenango have a total population of about 700,000 people of which about two-thirds are served from public water systems. These are provided by the cities independent of INFOM's program. The remaining 3,000,000 people in Guatemala live in rural areas. Only a small percentage of these people obtain their water from some type of public supply. Although the water use study areas will be located initially only in the smaller urban communities, the results will be applicable for design of water distribution systems to serve many of the one-third of the population not now served in the larger cities and many of the rural population as they tend to concentrate into the smaller urban communities and as they elevate their standards from fountain or courtyard type supplies to public water distribution systems.

The water demand study is clearly needed. It affects a very large number of people in a very direct way, not only in Central America, but throughout Latin America. To initiate the study in Guatemala where the Regional School of Sanitary Engineering is located has considerable advantages. Some of the faculty and the students who are from throughout Central America can participate in varying degrees in the study. Other participants in Guatemala could include INFORM and D.G. Obras Publicas. During my visit, formal and informal discussions were held with various staff members of the Regional School, INFOM, Obras Publicas, ROCAP, and the AID mission and all appeared quite enthusiastic about the water demand study and its proposed staged development in Guatemala and throughout Central America.

Following is a more detailed discussion of the data requirements, data collection, and data analysis for the study. In addition, some specific recommendations concerning these aspects of the study are made.

Data Requirements

The number of communities which should be studied depends on: (1) major classifications of type of facilities available such as whether the community has a sewer system or individual cesspools, or such as whether the community uses significant supplemental sources of water from springs, wells, or a nearby river or uses the public water system as the source for practically all water used, (2) the variation in average per capita or per connection use of water from community to community, and (3) the number of factors, over and above population, which significantly influence water use such as land use, economic conditions, weather, pricing, or other characteristics. Items (1) and (2) are important for the first and second stages of the study where the objective is to develop general estimates of water demands and their variability. Item (3) becomes important in the third stage where the objective is to develop a more elaborate design criteria which accounts for differences in water use between communities having different characteristics.

A minimum of four carefully selected study areas would be required in order to begin to assess the two alternative types of major classifications mentioned in item (1). Suppose water use is higher in areas with public sewers and higher where supplemental sources of water are insignificant. For design purposes, it may be reasonable to assume that a public sewer system will be constructed before the end of the design period for any proposed water system, or that the use of supplemental sources of water will gradually diminish as the people appreciate more and more the better quality water and more reliable service from the public system . Then, only water use data collected in such areas (having public sewers and essentially no use of supplemental sources of water) should be utilized to estimate water demands for design.

In considering item (2), if the variation in water use from community to community is high, then more communities (a larger sample size) must be studied in order to obtain results which reasonably can be used for prediction of water demands for design purposes. After water use data from the first several study areas in Guatemala have been analyzed, then fairly accurate estimates can be made of the total number of communities which should be studied both in Guatemala and throughout Central America in order to obtain reliable results.

For design of water systems under present practices, the estimated future population is multiplied by an average rate of per capita usage and the result is adjusted by a factor for maximum demand. Thus data on both average use and the variability in demand about that average must be collected and evaluated in this study.

The average use per connection in a given community or study area can be determined from individual meter records when services are metered. Metered services are a significant advantage in such a study because in areas where water service is on a flat-rate basis, master-meter records over a number of months would be required to measure average use per connection. In the first two stages of the study, water use per connection can be converted to water use per capita by estimating the average number of persons per connection based on present experience (probably 5 to 6). In the third stage field measurement of the family size may be necessary.

The variability in demand in a given study area on a seasonal and monthly basis also can be determined from individual meter records. However, the maximum daily and peak hourly demand, i.e. the variability in demand for much shorter time periods, are what is important in system design. These demands can only be measured by master metering and by periodic reading or recording of the registered accumulated use.

In addition, it will be necessary even in the first stage to assess the degree to which supplemental sources of water are utilized in meeting demands.

In the third stage, data requirements are considerably more extensive. It will be necessary to collect detailed field information on social conditions such as actual population, and family size; land use such as areas in cultivation per family or used for livestock; environmental factors such as rainfall and temperature; economic conditions, maybe based on the amount of taxes each family pays to the government; water pricing practices; and other data pertaining to the characteristics of the study areas.

Data Collection

An information sheet should be prepared for each community under consideration for study which contains the present number of connections and other data similar to that shown for each community in Table 1. In addition the sheet should include whether the community has a sewer system or uses individual cesspools, some assessment of the extent to which supplemental sources of water are used, and other information which influences the choice of the initial study areas such as ease of installation of of metering equipment, ability of the local system operator to take responsibility for the measurements, and ease of access for close management by Engineers Cordon and Samayoa especially during the initial phase of the study. Most of this background information is readily available and will not require extensive field investigation. After the communities to be studied are actually selected, follow-up field investigations on the data on the information sheet may be necessary as experience suggests.

The water use data needed to evaluate present design includes accurate estimates of the actual overall average water use, some assessment of the unaccounted-for water including leakage, and measurement of the variability in demand including the maximum daily and peak hourly demands.

In the communities under consideration for the initial stages of the study, all connections are individually metered. They are read routinely on a monthly basis for billing purposes. Thus, the actual overall average water use per connection for each community can be determined by summing the individual use per connection over a period of say a year and then dividing by the total number of connections included in the sum. This is an accurate estimate of the actual use. In order to estimate the size of the supply required, some assessment of unaccounted-for water would need to be made.

Inspection of the metered billing records in Ciudad Vieja suggests that the data can be readily obtained. In a community with 400 connections, the accumulated readings for 12 months amount to tabulating 4,800 readings in the field. These must then be converted to actual monthly use by taking the difference between successive readings. The yearly use can be more readily obtained by taking the difference between two accumulated readings a year apart. This should probably be done, but as a check on the computations because the monthly readings will be valuable for understanding monthly and seasonal variability and as a monthly check on the master meter readings. The collection of metered billing data for some of the communities should be initiated immediately.

The tabulations and computations involved in obtaining individual metered billing data susgests that graduate students in the Regional School of Sanitary Engineering might be effectively used as research assistants both to the get the job done and as an educational tool to enable them to better understand actual conditions in a water system. The computations also suggest that the data might be transferred to punched cards and processed on a digital computer.

The variability in demand on a daily and hourly basis needs to be assessed carefully because most components of a water distribution system are sized according to the magnitude of the maximum daily and peak hourly demand. In order to measure daily and hourly water demands in a community, it is necessary to install master metering equipment to monitor the flow of water as it enters the distribution system. Several alternative methods of master metering appear to be feasible for the needs of the study.

A meter could be installed in the pipeline on the demand side of the distribution system storage tank. In almost all the systems under consideration for study, the pipeline from the source, either pumped or gravity supplied, to the distribution system tank has no connections. Thus, measurement of the flow out of the distribution tank is a direct measure of the total demand in the system plus any leakage or unaccounted-for water. The simplest and least expensive meter would be of the propellor type with an accumulating register. This type of meter, however, has a comparatively narrow range of flows within which it records reasonably accurately. The wide range of flows from near zero at night to the periods of high use during the day essentially eliminates this type of meter from further consideration. The wide range of flows suggest that a compound meter, which is a combination of a propeller meter to measure the higher flows and a disc type meter to measure the smaller flows, and consequently has two accumulating registers, should be considered. These meters, however, are relatively expensive and the fairly small flows suggest another alternative.

A disc type meter is quite accurate even at flows as low as a few gallons per minute. They are available in sizes ranging from 5/8 inches to 2 inches. The larger meter has an upper limit of over 100 gallons per minute with only a small pressure loss across the meter. The estimated maximum demand at the present time in the communities under consideration for study amounts to less than 80 gallons per minute. This suggests that the desired accuracy could be obtained by installing one disc type meter up to 2 inches in size on the pipelines on the demand side of each distribution system tank. The size of the meters can be selected to measure present flows and so that there is reasonable excess capacity for growth in demands on the system. This solution will not be adequate, however, to meet all growth up to the design capacity of some of these distribution systems. As growth occurs and the flows approach the capacity of the disc meter, it is relatively easy where necessary to add another disc type meter in parallel with the first one. In this way the desired accuracy can be achieved with the least possible cost, and consequently this is the procedure recommended for master metering in this study.

Although the master meters could be read at periodic daily and hourly intervals to obtain the variability in demands, it would be desirable to install small recorders on the meters to obtain a continuous record of when the water was used. One such recorder is made by the Anderson Company of Muscogee, Oklahoma. Either 7-day or 2-day charts with hand wound clocks can be used. There is no ink involved because a stylus makes a line on the special paper of the charts. These recorders are placed on top of the meter in place of the meter register. The drive gear on the meter is meshed with a gear on the recorder to change the position of the stylus and rotate the chart. Adapter plates are available to enable the recorder to fit any size meter.

In situations such as San Lucas Sac, where there are some connections on the pipeline between the pumping station and the distribution tank, the system demands could be measured by a different procedure. A propeller meter could be installed on the pump discharge line where flows are within a narrow range and thus accurate results can be obtained. Then a water level recorder could be installed at the distribution system tank and the flows into and out of the tank can be computed. From this information, the demands on the system would then be determined, but the data reduction in this case is somewhat more complicated. All of the readings from master metering and recording equipment will be useful in the operation of the system. Metering the pump output and recording the level of the tank is slightly more advantageous than metering the outflow on the demand side of the distribution tank from the point of view of providing direct information to the system operator. In addition, a master meter on the pump discharge line has the advantage that unaccounted-for water from the entire system could be assessed including any leakage from the pipeline between the pump and the distribution tank. Students from the Regional School could also help with the reduction of data from the charts if this type of procedure is used to determine demand. Such analysis, again, can be very educational to the students. Also, thinking in the long term, such equipment could eventually lead to automatic turning on and off of the pump when the tank is low or near full, respectively.

In the third stage of the water demand study when the various factors which influence water use in different communities will be investigated in detail, it will be necessary to collect field data on land use, economic conditions, family size, weather conditions, water pricing practices, and other factors. In this stage, public health officials, the operator of the system, the local priest, and others might be good sources of information and might be asked to assist in the data collection within each study area.

Thus the data collection in the first two stages of the study will be directed at obtaining primarily water use data, and general data about the communities which do not require detailed field investigation. Other than water use data, detailed field investigations will not be necessary until the third stages of the study.

Data Analysis

As the first stage of the study progresses and data becomes available on both the average use from individual meter records and the variability in demands from master meter records, Engineers Cordon and Samayoa can begin to compare the initial results of the study with the present design practice. From the data available, they can estimate average water use and peak to average ratios which might be used in design and thus indicate early in the study the benefits which can be achieved. This can serve as a basis to obtain additional financial support for the study where necessary.

Careful interpretation of the initial results must be made. As an example, suppose it is found that average per capita use in say six study areas is 132 liters per capita per day. This number cannot be suggested for design purposes because probably one-half of the study areas, or three, had a use lower than 132 and probably the other three had use higher than 132. The average was 132, but for design the variation from area to area needs to be taken into account. Suppose the variation suggests that with a reasonable degree of probability the predicted use is likely to be 132 plus or minus 25 liters per capita per day. Then maybe 160 liters per capita per day ought to be proposed as an average water use figure for design purposes in these types of communities.

Also, after the data from the first stage have been analyzed, estimates can be made of the adequacy of data collected to achieve the desired results and of the needs for additional data with respect to: (1) the type of additional study areas needed such as having public sewer systems if the water use is higher in such areas and hence only data from such areas would be used to predict design requirements, (2) the number of study areas needed of the type desired, and (3) the duration of the data collection period in the then existing study areas. Engineers Cordon and Samayoa should work closely with the statistician on the staff of the Regional School in this regard.

After the water use data from the second stage have been analyzed, more specific recommendations can be made concerning average use and peak to average ratios to be used for improved design of water distribution systems. In the third stage, the data analysis will enable Engineers Cordon and Samayoa to assess the relative importance of the major factors which influence water use and can suggest those factors over and above the population to be served which might be used in prodiction of water demands for design purposes. Throughout all stages, they should work very closely with D. G. Obras Publicos and should keep INFOM fully informed of progress. In addition, they should work very closely with the appropriate individuals in the other Central American countries both to keep them informed of progress in Guatemala and to assist in the development of study areas in these other countries. Both Engineers Cordon and Samayoa can work very closely with the students at the Regional School who may be participating in the project in various ways.

They should also maintain close contact with Mr. Donald Lauria at the University of North Carolina who is considering utilizing data from the third stage of the study as a basis for his doctoral dissertation, which involves a more extensive statistical analysis of the data in order to assess the relative influence of each factor. His thoughts during the first and second stages of the study could simplify and improve the chances of achieving success in the third stage of the study.

The opportunities for this study to have a significant impact on the overall design of water distribution systems are many. A water system is one of the most basic public works in almost any community. Thus the number of people affected is very large. The trend toward urbanization increases the need for expansion and development of adequately designed water distribution systems. Significant monetary resources could be devoted to serving even more people with water or reallocated to meet other needs as a result of a better understanding of water demands and an improved system design criteria. Guatemala and the other Central American countries working through the Regional School of Sanitary Engineering can lead the way by successfully carrying out this carefully staged water demand study.

F. Pierce Linaweaver, Jr.

Table 1. List of Possible Study Areas, Guatamala, C. A.

Community	Type of Supply	Population 1964 Census	Design Average Demand (liters/sec)	Diameter of Supply Main from Distribution Tank (inches)	Minimum Pressure (meters)	Q_{max} (liters/sec)	No. of Connections as of June 1966	No. of Homes in 1964 (2)
1. San Agustín Acasaguastlán	Grav.	3113	8.85	6" & 4"	13	17.7	39%(5) 232 (45%)	520
2. San Francisco Zapotitlán	Grav.	1393	3.26	4"	14	6.52	115 (50%)	230
3. Teculután	Pumped	1723	4.18	6"	9	8.36	180 (63%)	287
4. Ciudad Vieja	Pumped	5721	7.17	3" & 6"	15	3.74 10.60	492 (53%)	950
. San Miguel Petapa	Pumped	2035	3.71	6"	10	7.42	296 (83%)	355
6. La Gomera	Well	1397(1)	3.60	6"	9	7.20		234
7. San Raymundo	Well	1601	3.73	6"	13	7.46	97 (37%)	265
8. Salcajá	Pumped	5271	11.00	4" & 6"	17	6.14 13.86(3)	98 (11%)	880
9. San Rafael Pié de la Cuesta	Grav.	1407	2.36	2" AC	19	4.72	95 (40%)	235
10. San Lucas Sac.	Pumped	1567	5.19	6"	8	12.48	153 (59%)	260
11. Momostenango	Grav.	3148	6.04	3" & 4"	18	2.72 9.36	98 (19%)	525
12. Santa Ana Huista	Grav.	940	2.54	3"	13	5.08	86 (55%)	156
13. San José La Arada	Grav.	908	1.58	4"	5	3.16	74 (49%)	152
14. Asunción Mita	Grav.	6341	18.35	10"	5	21.76(4)		1050
15. Usumatlán	Pumped	813	2.65	4"	13	5.3	144	136
. Monjas	Pumped	2857	5.99	6" AC	15	11.98		475
17. Jicaro	Grav.	1636	5.31	4"	23	8.17	185 (68%)	272
18. Quezada	Grav.	1499	4.72	4" AC	16	9.44	204 (82%)	250

1. Without including Chipilapa.
2. Population 1964÷6
3. Pipelines from the tanks, not from the wells
4. Only for gravity supply line
5. Per cent of homes connected assuming no growth in homes since 1964.

APPENDIX B

EVALUATION OF PUBLIC WATER SUPPLY HEALTH BENEFITS IN DEVELOPING COUNTRIES

EVALUATION OF PUBLIC WATER SUPPLY HEALTH BENEFITS IN DEVELOPING COUNTRIES

CONTENTS

EVALUATION OF PUBLIC WATER SUPPLY HEALTH BENEFITS IN DEVELOPING COUNTRIES

1. INTRODUCTION

Planning may be defined as "an organized conscious and continual attempt to select the best available alternatives to achieve specific goals" (1). In general, a hierarchy of goals exist for those who plan. In the case of public investment planning, the ultimate goal is usually the maximization of national welfare. Hence, public agencies charged with the responsibility of investment planning are faced with the tasks of (1) conceiving and formulating alternative projects which will improve welfare, and (2) selecting from among those projects the ones which make the greatest improvement in welfare, taking into account budgetary and other constraints which have limiting effects.

In the United States and a few other countries most of the water supply and other public planning is done at the local government level. Those who plan at this level must consider alternative investment projects and select from among them the ones which do most for improving the welfare of local citizens. In such cases, water supply projects must compete with relatively few other investment projects, and the task of decision making to allocate the municipal budget among these projects is often not too difficult since the number of alternatives is small.

However, such is not the case in most countries of the world and particularly the developing countries. There, most public planning is performed by a central agency of the national government, and the alternative investment programs and projects are numerous and varied. Competition for implementation is keen, and the decision problems are much more difficult than in the case of local planning.

Within recent years, much progress has been made in the field of benefit-cost analysis to develop methodologies for improving public investment planning (2). In brief, the process consists of ranking alternative projects by means of an investment criterion which focuses on benefits* and costs and then selecting those projects for implementation which lie within budgetary and other constraints and which maximize the total value of the criterion.

Although benefit-cost analysis has generally made improved decision making possible, its value is limited by ability to develop monetary benefits for the alternative projects. In cases where projects produce outputs which are purchased in the market place, it has been possible to obtain fairly good measures of monetary benefits. However, in the case of social overhead projects such as public water supply, this has not been possible, and planners have turned to other means of expressing benefits.

In the early 1960's, a classic attempt was made to assign monetary benefits to public water supply in Puerto Rico (3). The researchers, using concepts from Weisbrod (4) and Dublin (5), sought to express benefits in terms of additional worker income which results from reduced water associated morbidity and mortality following construction of public water systems. This work was primarily concerned with the methodology of assigning benefits. Hence, the researchers used real data where possible but made rather large assumptions regarding the specific health improvements associated with public

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*Benefits are defined as the monetary value of positive project gains which satisfy planning objectives.

systems. Consequently, the results of the study which specifically relate to Puerto Rico are of somewhat limited value, but the methodology and approach are significant since they focus attention on the need to accurately determine the health effects of public water supply, and they indicate how such data can be used in the rational planning of new systems.

Although the association between water and health has been extensively studied and well documented*, the relationship between improved community health and public water supply is less well understood. Few studies have been made to evaluate the health effects of public supplies, and consequently this paper presents some considerations for the design of epidemiologic studies to obtain such information, primarily in developing countries.

2. PROGRAM EVALUATION AND THE EPIDEMIOLCGIC METHOD

The type of study under consideration here is an evaluation of public water supply programs. Evaluations may be made from several points of view and at different levels. One classification (6) distinguishes assessments of need from assessments of accomplishment, and **three** evaluation levels are considered: (1) value of the program to those who receive its services (2) appraised worth of the program in meeting stated goals and objectives, and (3) value of the program when measured against accepted scientific standards. This classification of evaluation is similar to that of Hutchinson (7) who distinguishes between (1) review, (2) demonstration and (3) experimental studies. Clearly, the type of evaluation in mind here is assessment of accomplishment at the highest level (ie, against scientific standards) which corresponds to Hutchinson's experimental study.

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* <u>Water and Man's Health</u> by A. P. Miller, AID, Washington, D. C. (1962) lists over 250 references.

The scientific method has been variously described by different authors. Although some differences in definition exist, there seems to be general agreement that it includes the following essential elements which form a circular pathway: (1) observation (2) formation of hypotheses (3)testing of hypotheses (4) induction of new theory (8). Whereas the scientific method has generally been associated with experimental studies for understanding natural phenomena, one of its counterparts in the social science field is the epidemiologic method which generally relies on an observational rather than experimental approach. One classification of the basic steps in observational science - according to Cassel (9) - is the following: (1) generalization (2) hypothesis formation (3) classification (ie, division of samples into sets of those with and without the characteristics or conditions of interest) (4) data collection and processing (5) analysis and interpretation of results. It is the purpose of this paper in the succeeding sections to investigate how an evaluation study of public water supplies conforms to the major steps in the above pathway.

3. BASIS FOR HYPOTHESIS

Although few modern epidemiologic studies have been made to evaluate the health effects of public water supply, there are some citations in the literature which imply or show such association. One of the most classic is that reported by Leach and Maxcy (10) who attributed relatively low typhoid fever prevalence in large U. S. communities to good sanitation practices including public water supply. Dr. Abel Wolman (11) has tabulated the historical prevalence of typhoid in the U. S. and has compared these rates with the number of public water supply systems to demonstrate the association between increasing numbers of systems and reduced typhoid morbidity. Documents of the World Health Organization (12) cite instances in Teheran, Karachi and other places where implementation of public supplies has caused striking reduction of water borne diseases. Hence, it seems entirely reasonable to hypothesize that improvements in community health are associated with public water systems.

4. HYPOTHESIS FORMATION

4.1 Nature of the Hypothesis

The above hypothesis is a very general statement, and as it stands cannot be tested. It is necessary to sharpen the hypothesis by transforming it into an equivalent statement which includes quantifiable parameters (13). Specifically, it is necessary to select criteria which are measures of "health" and "public water systems". For example, does "health" refer to absence of typhoid, dysentery, cholera, or what? How much "health" are we talking about? Are "public water systems" those which employ treatment, public fountains, Fordillas*, piped services, or combinations of these?

We see from the above that the hypothesis must ultimately be an explicit statement which relates health changes to public water systems. Using modern epidemiologic concepts based largely on statistics, the general hypothesis will be transformed into a mathematical statement which relates "health" (the dependent variable) to a set of independent variables, of which "public water systems" constitute a subset. At this point, it is necessary to note that the set of all factors (or criteria) which have hypothesized association with the dependent variable constitute the set of independent variables.

Having explicitly selected the dependent and independent variables, the investigator must express the hypothesized interrelationships among them by means of a parametric mathematical model, and only then is the work of hypothesis formulation complete.

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* A "Fordilla" is a specially designed spring - loaded faucet manufactured by the Ford Meter Box Co., Wabash, Ind. cf "New Concept in Water Service for Developing Countries" by Borjesson, E. K. G. and C. M. Bobeda, JAWWA, V 56, n 7, p 853, July, 1964.

Under the succeeding items of this section, consideration will be given to the dependent and independent variables and selection of corresponding criteria.

4.2 Dependent Variable

Under the general hypothesis, it is assumed that higher quality of health exists where public water systems have been implemented than where they are absent. This implies that lower disease prevalence is associated with public systems. It also implies that the incidence of disease is lower in those communities where water systems have been constructed.

Hence, we shall adopt disease prevalence and incidence as a measure of health. The question now is what disease or diseases? For ease of study and analysis purposes, a single disease might be selected instead of several. This limits the statistical analysis to univariate response models. Based on studies in the U. S. and abroad (14, 15), the single disease which is suggested is diarrhea which is defined as abnormal frequency or liquidity of the stools. In the Costa Rican study cited above, diarrhea was determined by (1) interview and (2) laboratory examination. A more complete description of field measurement of the dependent variable will be presented in section 5 of this paper.

4.3 Independent Variables

When viewed absolutely, the prevalence of diarrhea in a community is a function of independent variables which may be classified in five categories: (1) sanitation conditions, (2) social conditions, (3) economic conditions, (4) climatologic conditions, and (5) geographic conditions. Hence, if one desired to postulate a complete model describing the association between diarrhea and the variables upon which it depends, the model would have to include quantifiable factors from each of the above categories. As might be expected, difficulties are often encountered in selecting suitable factors to represent some of the conditions, particularly the social, economic, and even geographic ones. However, some work has been done (16, 17, 18) on developing indices which reflect such conditions and these appear suitable for the study proposed herein.

Our hypothesis focuses only on a subset of sanitation conditions, viz, public water supply. Hence, the primary independent variables to be included in the model will be those associated with this characteristic. The influence of factors in the other four categories on diarrhea will be eliminated in the proposed study to as large extent possible by carefully selecting communities so that these other factors are constant rather than variable. That is, controlled studies will be made such that only factors of interest are allowed to vary, the factors being those associated with public water supply.

Under the general hypothesis, the primary variables of the model are those associated with the quality of water supply service in communities. Hence, it is proposed that three variables be used to represent the following conditions: (1) public fountain systems (2) Fordilla systems (3) systems of piped water into dwelling units. It is important to note that each of these are discrete dichotomous variables; ie, public fountains (and the other services) either exist or not. Hence, in a statistical model, these variables take the value zero or one to indicate absence or presence of the system. All variables equal to zero implies no public system.

From the above, we would conclude that with suitable control, our hypothesis postulates a functional relationship between rates of diarrhea and the variables representing types of supply service. However, such a model would completely overlook the possibility of secondary and other associations. Hence, the hypothesis (and corresponding model) ought to be expanded to answer such questions as: What effect does water quality have on diarrhea? What are the effects of public sewers? What are the socio-economic effects? Correspondingly, it would be necessary to expand the number of independent variables in the model to include those additional factors suspected of being most significant. In the case of water quality, it is proposed that a single continuous variable, concentration of Escherichia coli be introduced. The effect of sewers may be taken into account by a single dichotomous variable, and socio-economic effects may be considered via a continuous index of the form referenced above (17). Hence, study control of the type initially described above would have to be relaxed so that the effects of all independent variables could be investigated.

5. TESTING THE HYPOTHESIS

5.1 Classification

In order to test the hypothesis, it is necessary to select communities with suitable characteristics so that all the factors of the model can be evaluated. For the independent variables listed above, the complete tableau of required community characteristics, assuming balanced study design and only two levels of socio-economic index (high and low) and two levels of water quality (high and low) is as follows:

Service	NONE				FOUNTAINS				FORDILLAS				PIPED			
Sewers	Yes		No		Yes		No		Yes		No		Yes		No	
Soc.-Econ.	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Quality H																
Quality L																

From this tableau we see that thirty-two different communities would be required for the study. If socio-economic level were eliminated as a variable, (ie, communities were selected so as to control this factor at a constant level), the required number of communities would be reduced to sixteen. If, in addition, the communities with Fordillas were eliminated, the required number of study sites would be twelve. If both fountains and Fordillas were eliminated, the number would be eight, and if quality was controlled, four. Of course, any combination of the above would also be possible, depending on the degree of complexity of the hypothesis. As is immediately apparent, resource requirements for the study increase tremendously as the number of variables in the model increase. It is interesting to note that a recent study proposal for evaluation of public water supplies in only six Peruvian towns estimated time requirements at three to four years (19).

An integral aspect of classification is the type of study to be performed. As used herein, studies may be classified dichotomously as prospective or retrospective. Prospective studies offer certain advantages over retrospective ones, but they are relatively expensive in time and other resources (20). Assuming control of all factors except type of water supply service, a fully prospective study would consist of selecting matched pairs of communities, all initially without public supplies but such that a public system would be implemented in one of the towns of each pair in the near future. Cross sectional studies would then be performed to determine existing diarrheal prevalence, and those persons without diarrhea would comprise the study sample of interest. Following construction of water systems, both groups (those with and without public water) of only those without the disease would be studied to determine incidence levels of diarrhea, and conclusions regarding the effects of public water on diarrhea would be drawn accordingly.

A modified prospective study of the type made to evaluate the effects of bathing water quality on health (21) would be far less costly and probably only slightly less valuable than the above. Such a study might be identical to the above except that the communities would be selected so that the public supply systems would already be in existence. Probably the least expensive study would be a case history study in which basic classification was according to presence or absence of diarrhea. As in the prospective type, such a study could be made with proper selection of communities.

5.2 Gathering the Data

In the complete model postulated above, diarrhea rate is a function of the type of water supply service, the existence of sewers, socio-economic level and water quality. With exception of the dependent variable and water quality, the above factors are associated with community characteristics and need only be measured or observed at the time the study communities are selected. As a result, once selection has been made, data collection is reduced to determination of water quality and disease rates.

The task of water quality measurement is not particularly difficult since only one factor is under consideration, viz coliform density. In those cases where public systems exist, it is proposed that water samples be taken at various points in the distribution system two or three times each week during the initial stages of the study to determine quality levels. After patterns of quality have been observed, sampling frequency might be reduced to once weekly. Where public systems do not exist, the sources of water should be sampled according to the above schedule, and for all communities, random sampling of of water stored in dwelling units should be done.

Determination of disease levels presents more serious problems. In both the Tecumseh (22) and Costa Rica (14) studies, health levels were determined by a questionnaire, physical examinations and laboratory analysis. The results obtained were much more satisfactory than those of the bathing water quality study (21), which relied solely on the use of forms submitted by study participants. Correspondingly, there was a significant difference in the costs of the studies.

The methodology of the Costa Rica study seems to have produced very good results, and hence, with slight modification is the recommended procedure for the study proposed herein. In the above referenced study, a complete census was made of the study communities. The age and sex of members of all households were determined. All houses were then numbered on a map and a random table used to select ten percent of the houses for study purposes. Diarrhea was determined by weekly visits of a public health nurse. For reported cases, a stool sample was obtained, if possible, or a rectal swab. The presence of enteric infection was confirmed by analysis of samples and swabs for *Shigella*, *Salmonella*, and pathogenic *Escherichia coli*. In addition, similar data were obtained on all patients who visited community diarrhea clinics which were maintained in operation throughout the duration of the study.

5.3 Data Processing

The processing of data constitutes a major work of the study and will be given only cursory attention herein. It has already been assumed that a mathematical model was hypothesized to represent the association among variables. Data processing would then consist of evaluation of the parameters of the model. Such evaluation would most suitably be made by some form of regression analysis or analysis of variance. As periodic analyses indicated the significance or insignificance of study factors, methodology would be correspondingly changed to focus more attention on those factors which were found to be most important.

6. SUMMARY

In developing countries, the competition for implementation among alternative public investment projects is keen, but the problems of decision making might be eased through use of benefit cost analysis. It has been proposed that the health benefits of public water supply systems might be measured as the wage value of water associated morbidity and mortality avoided following construction of such systems. Hence, the research proposed herein is for an epidemiologic study to determine the extent to which health is improved by public water systems.

The first step in the study is the formulation of a mathematical model including quantifiable factors which represent the hypothesized association between water and health. A fairly large model was considered which associated diarrhea (the dependent variable) with four levels of water service quality, the existence or absence of sewers, two socio-economic levels, and two water quality levels. The required number of communities to test such a model is 32 which would probably be prohibitively expensive. A more modest model could be formulated by controlling for as many of these factors as desirable.

Once the model representing the hypothesis was made, communities with suitable characteristics would have to be selected. Following selection, the bulk of field work would consist of evaluating diarrhea levels and water quality (assuming this factor was kept in the model as a variable).

Water quality measurements would consist of making E. coli determinations on samples collected at the source, within the distribution systems, and within homes on some assigned frequency schedule. Diarrhea measurements might rely primarily on the work of public health nurses or others who would make once weekly visits to a selected sample of homes in each community. Verbal indications of disease would be confirmed where possible by physical and laboratory analysis. Final data processing would probably rely on computerized regression analysis.

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