TECHNICAL REPORT



# DERIVING DESIGN STANDARDS FOR RURAL WATER SYSTEMS

## CASE STUDIES USING WATER DEMAND DATA FROM ECUADOR, GUATEMALA, AND HONDURAS



WASH Technical Report No. 78
September 1992

WATER AND SANITATION for HEALTH PROJECT

Sponsored by the U.S. Agency for International Development
Operated by CDM and Associates

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Prepared for the Office of Health,
Bureau for Research and Development,
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by

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and
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## ACRONYMS

| | |
|---|---|
| A.I.D. | U.S. Agency for International Development |
| gal | gallons |
| gpcd | gallons per capita per day |
| gpd | gallons per day |
| gph | gallons per hour |
| gpm | gallons per minute |
| hr | hours |
| jpm | gallons per minute |
| LACD | long-term average per capita demand |
| LAD | long-term average demand |
| MDPF | maximum daily peaking factor |
| MHPF | maximum hourly peaking factor |
| OLS | ordinary least squares |
| POP | population |
| STV | storage tank volume |
| WASH | Water and Sanitation for Health Project |
| WS&S | water supply and sanitation |

## ACKNOWLEDGMENTS

The authors thank Frederick Mattson, CDM International and formerly on the WASH Project staff, for his support and help with this project. Without his involvement, this research could not have been done. Thanks are also due to the A.I.D. mission and country engineers who assisted in this work. They supervised installation of meters and collection of field data, intervened with field staff when problems arose, and arranged for data to be reviewed and sent to the United States for analysis. In Ecuador, the engineer who was particularly helpful was Adalid Arratia (A.I.D.); in Guatemala, engineers Alfredo Szarata (A.I.D.) and Carlos Calderon (Ministry of Public Health); and in Honduras, engineers Carlos Flores (A.I.D.) and Nelson Flores (formerly of SANAA). Finally, thanks are due to the many field enumerators who made and recorded the meter readings upon which this project is based.

## ABOUT THE AUTHORS

Donald T. Lauria is Professor of Water Resources Engineering in the Department of Environmental Sciences and Engineering at the University of North Carolina where he has been a faculty member for 27 years. His main field of interest is community water supply and sanitation planning in developing countries. In recent years, his research has focused on estimation of household willingness to pay for improved water supply and sanitation using the contingent valuation method. For many years he has been concerned with design standards for LDCs, including development of mathematical models and computer programs for optimal decision making. Dr. Lauria has worked in numerous countries of Latin America, Southeast Asia, and Africa for the World Bank, PAHO, CDM-WASH, and other agencies.

Kimberley D. Cizerle graduated from North Carolina State University in 1989 with a B.S. in nuclear engineering. After working with the Environmental Sciences group of Carolina Power and Light Company, she decided to pursue a career in environmental engineering. She attended the University of North Carolina at Chapel Hill, graduating in 1991 with an M.S. in environmental engineering; this report constitutes part of her master's thesis research. She is currently an associate engineer with ENVIRON Corporation in Princeton, New Jersey. Her projects include planning hazardous substance discharge prevention strategies for industries, analyzing environmental site characterization data, and planning and designing remedial actions for industrial sites with contaminated soil, sediments, and/or groundwater.

# EXECUTIVE SUMMARY

This study was conducted to evaluate design standards for rural water supplies in Ecuador, Guatemala, and Honduras. Special emphasis was placed on those supplies assisted by the U.S. Agency for International Development (A.I.D.). The ultimate goal was to produce results that can be applied throughout much of Latin America and beyond.

During the 1980s, A.I.D. provided grants and loans in the above three countries of more than $50 million to assist with rural water supplies. From 1990 to 1995, A.I.D. has promised to spend $85 million on new systems in Central America. Overall, hundreds of millions of dollars will be spent in Latin America during the next decade on community water supply and sanitation. Globally, the amount is in the billions of dollars.

The key determinants of water system costs are the standards used for design. Such standards underlie the decisions that are made about the capacities of system components: source works, transmission mains, storage tanks, and distribution networks. Some of the key standards include the average per capita design flow, maximum daily and maximum hourly peaking factors, and the detention time for storage tanks at average design flow.

Despite the enormous investments that have been made in rural water supplies, meters are rarely installed in new systems, and consequently data are unavailable on actual water use. As a result, designers make assumptions and judgments as the basis for design standards. The approach is not so much "normative" (the amount of water that should be used) as it is predictive (the amount of water that is expected to be used). Without data on actual use, the risk is high that design standards will be inaccurate (i.e., that standards will differ from actual use).

The main purpose of this study was not to question whether the philosophy of trying to meet water needs is correct. Rather, taking that philosophy as given, the purpose was to test the assumptions and judgments on which capacities (and costs) are based against actual field measurements of water use and to show how to revise standards, if necessary.

Starting in 1989, meters were installed in 16 communities in Ecuador, Guatemala, and Honduras with populations of approximately 100 to 1,200 each. During a period of two months in each town, local personnel were hired to read the meters every 15 minutes on a total of 30 days. The meter readings were analyzed at the University of North Carolina to determine such parameters as average per capita demand, maximum daily and maximum hourly demands, and storage requirements to meet demands. The results from the 16 communities were pooled and regression analyses made in order to develop equations for predicting the key design parameters to use for towns of all sizes in the three countries.

The study showed that simple and relatively inexpensive data collection efforts can yield a basis for design standards that reflects actual local conditions. The sample of communities was too small to enable definitive statements about the effects of such specific factors as climate and socioeconomic conditions on water use, however. Similarly, the periods of data collection were probably too short to capture entirely the daily and hourly variations of water use within various systems. Nevertheless, the study provides a database that far exceeds existing knowledge about actual patterns of water demand in Ecuador, Guatemala, and Honduras.

Actual per capita demands, especially in Honduras and Ecuador, are significantly higher than the standards being used for design. In light of the millions of dollars being invested in rural water supply and sanitation, this discrepancy points to the urgency of re-examining current planning policies and standards.

Several recommendations emerged from the study. For example, master meters should be installed in new and existing systems. For most towns, a meter would represent less than 1 percent of total system cost. Studies of the type described herein should be conducted routinely, preferably led by local universities, with support from A.I.D. and other donors. The findings from this study should be used to update current design standards. Professional meetings should be held annually for the next three to five years to plan replication of this study, compare findings, and update design standards.

# 1

## INTRODUCTION

The study reported herein was conducted in three countries of Latin America: Ecuador, Guatemala, and Honduras. The intent of the study was to obtain data that would have implications and value not only in these countries but throughout much of Latin America and beyond. The study's chief concern was with design standards for rural water supplies, especially those systems that receive assistance from the U.S. Agency for International Development (A.I.D.).

In the 1980s, massive investments were made in constructing water supply and sanitation (WS&S) systems in the rural communities of developing countries. In the three countries where this study was conducted, more than 800 towns were served with new systems, and 100 or more had their existing systems rehabilitated. A.I.D., only one of several donors, provided grants and loans in these three countries totaling more than $50 million. These were matched more than one-to-one by host governments and local communities (Burns and Mattson, 1989; Edwards et al., 1989; and Moncada et al., 1986).

Such investments are continuing into the 1990s. In Central America, for example, rural WS&S systems planned for construction between 1990 and 1995 are estimated to cost about $320 million, of which $85 million has been promised by A.I.D. (Ey, 1990). Given that design standards play a key role in the cost and functioning of water systems and user satisfaction, and given the magnitude of future investments in this sector, not only in Latin America but throughout the world, the question of standards is timely and important.

The characteristics of A.I.D.-assisted rural WS&S systems in the countries of this study as well as many other nations are remarkably similar. A few features in particular are noteworthy: water supplies are usually derived from their source by gravity, and delivered to customers via individual yard taps. Each house is provided its own latrine. The water systems are not equipped with master meters, so data are not collected on actual water use. Households are usually charged a flat-rate tariff each month (less than $1), but in order to curtail excessive use, households are asked not to use water from the piped system for gardens or animals.[a]

The design offices in each country usually have their own standards for deciding the capacities of new water systems; and A.I.D. approves these standards in cases where it provides financial assistance. Typical standards for deciding capacities are as follows. Population is assumed to

[a] Some systems in Ecuador have individual house meters that incur a two-part tariff: a flat rate for an initial quantity plus a per gallon charge for excess use. However, the tariff was not enforced in the communities that were studied, effectively resulting in a flat-rate tariff for those households.

increase about 2 percent per year, and systems are designed to meet water needs 20 years in the future. If the current population of a community that is to receive a new system is, say, 1,000, the predicted population 20 years hence is about 1,500, which is the population for which the system is designed. With water distributed by yard tap, it is usually assumed that about 25 gallons per capita per day (gpcd) on the average will meet needs. Hence, for a design population of 1,500, the average design flow would be about 37,500 gallons per day (gpd) or 1,600 gallons per hour (gph).

Water use in communities varies from one hour to another and from one day to the next. Consequently, sources of supply are typically selected with capacity equal to at least 1.5 times the average design flow. For the example above, required source capacity would be about 56,300 gpd or 2,300 gph. Similarly, piped distribution networks are designed to meet peak hourly flows, which are often assumed to be about 2.5 times the average design flow. For the given example, the peak hourly design flow would be about 94,000 gpd or 3,900 gph. Storage tanks are provided to supplement inflow from the source to meet peak hourly demands and are typically sized to provide about 8 hours (hr) detention time at average design flow. For the example above, required storage tank volume is about 13,000 gallons (gal).

Without master meters in water systems, standards such as those listed above are usually based on the estimates of the designers, and are frequently influenced by the standards of other countries, which may or may not be based on actual measurements of water use. To determine appropriate design standards, engineers in developing countries hold workshops and seminars to gather information.

The prevailing attitude among engineers is that systems should have sufficient capacity to meet the water needs or requirements of the users during the design period, at the end of which time a capacity expansion will be needed. The engineer's approach, then, is not so much "normative" (the amount of water that people should be using) as it is predictive (the amount of water it is assumed the people will use given gravity supply, individual yard taps, a flat-rate tariff, and prohibitions against using the water for gardens and animals).

The main purpose of this report is not to question whether the design philosophy of trying to meet water needs is correct. Rather, taking that philosophy as given, the purpose is to test the assumptions and judgments on which capacities are based against actual field measurements of water use and to show how to revise standards, if necessary. A companion report, "A.I.D.'s Rural Water Program in Latin America: What to Do about High Demand," WASH Technical Report No. 79, addresses the more serious question of planning policy and whether the requirements approach to design is appropriate.

# 2

## STUDY DESIGN AND FIELD PROCEDURES

Planning for this study began in spring 1989. Contacts were made with engineers in charge of the rural WS&S programs in the A.I.D. missions of Ecuador, Guatemala, and Honduras to explain the study's goals and methodology and to seek local cooperation. Help was solicited for selecting candidate study sites in each country.

The criteria used for selecting sites were as follows: (1) the system should be recently constructed and supply water by gravity; (2) the system should be functioning properly, preferably with excess capacity, and be providing water 24 hours per day, (3) the chosen communities should reflect geographic diversity (e.g., hot, temperate, and cold climates) and socioeconomic diversity; and (4) water use should be restricted to domestic consumption.

In September 1989, visits were made to Guatemala and Honduras to begin field work and data collection; Ecuador was visited in May 1990. To measure water use on a community-wide basis, several macrometers were taken to each country. These were Hershey volumetric MVR-160 meters with a maximum 160-gallons-per-minute (gpm) capacity calibrated in gallons (gal). The meters' readouts are similar to those on a car odometer.

In the three countries studied, 10 meters were initially installed in 10 different communities. Some of these were later moved to other communities. Altogether, the study covered 16 separate towns, the basic information for which is shown in Table 1.

In each system, the meter was installed in the transmission main that fed the distribution network from the storage tank. Due to cost, it was not possible to purchase automatic meter recorders nor to pay workers to read the meters 24 hours a day continually. Consequently, two people in each community were employed and taught how to read the meter and record its readings on the appropriate data forms.

Town water committees consistently indicated that most consumption occurred during daylight hours, from just before sunrise until after sunset. Hence, the hours from 4:00 a.m. to 8:00 p.m. were selected as the meter-reading time period, during which the two meter readers each worked eight hours, making meter recordings every 15 minutes. The first worker recorded meter data from 4:00 a.m. until 11:45 a.m. and the second worker from 12:00 noon until 8:00 p.m.

At the outset of the study, the meters were read every day for two weeks. After this initial period, they were read every other week for 7 days straight, 16 hours per day. At the end of a week of readings, a final reading was taken at 4:00 a.m. on the following day so that seven consecutive 24-hour periods were covered. Table 2 shows the dates and times of meter readings for the 16 communities studied.

**Table 1**

**Communities Where Meters Were Installed**

| *Town* | *Population* | *Climate* | *Town Name Code** |
|---|---|---|---|
| Guatemala | | | |
| Calera Tenerias | 348 | cold | CAL |
| Chuicotom | 372 | cold | CHU |
| Xetacabaj | 432 | cold | XET |
| Nueva Esperanza | 804 | temperate | NUE |
| La Cienaga | 840 | cold | LACI |
| Honduras | | | |
| La Bella Vista | 140 | hot | BEL |
| La Curva | 260 | hot | LACU |
| Coloraditos | 350 | hot | COL |
| Brisas del Carmen | 408 | hot | BRI |
| Quebrada de Yoro | 819 | hot | QUE |
| Ruth Garcia | 850 | hot | RUT |
| Colonia Martinez | 960 | hot | MAR |
| Ecuador | | | |
| Unachi-Pucara | 245 | cold | UNA |
| Panzaleo | 252 | cold | PAN |
| San Vicente de Guayllabamba | 820 | temperate | SAN |
| Tandapi | 1,243 | temperate | TAN |

* Code names are used throughout the remainder of this report.

Once a week or so, the data forms were retrieved from the meter readers by one of the engineers working on the project and brought to the A.I.D. mission for mailing to the United States. Upon receiving them, the authors of this report checked them for errors and read the raw meter readings into the computer. Checking proved to be straightforward, as the frequently recorded readings seldom changed, making anomalous results easy to detect. In a few cases, meter readers had to be reinstructed after making mistakes. This was done by local engineers. In one or two instances, readers had to be dismissed for incompetence. All the readers had formal contracts for their services and were paid an amount at least equal to the local wage rate, which provided a basis for requiring satisfactory performance.

**Table 2**

Dates and Times of Meter Readings

| Town | Start Date | End Date | Days of Data | Period of Reading |
|---|---|---|---|---|
| Guatemala | | | | |
| CAL | 26 Aug 90 | 4 Nov 90 | 35 | 4 a.m.-8 p.m. |
| CHU | 14 Oct 90 | 23 Dec 90 | 35 | 4 a.m.-8 p.m. |
| XET | 4 Jan 90 | 20 Jan 91 | 34 | 4 a.m.-8 p.m. |
| NUE | 5 Jan 90 | 18 Jan 90 | 1 | 6 a.m.-9 p.m. |
| LACI | 3 Jan 90 | 16 Jan 90 | 13 | 5 a.m.-8 p.m. |
| Honduras | | | | |
| BEL | 30 Sep 90 | 13 Jan 91 | 46 | 4 a.m.-8 p.m. |
| LACU | 1 Oct 89 | 6 Oct 89 | 4 | 5 a.m.-8 p.m. |
| COL | 1 Oct 89 | 15 Nov 89 | 15 | 5 a.m.-8 p.m. |
| BRI | 1 Dec 89 | 14 Jan 90 | 14 | 5 a.m.-8 p.m. |
| QUE | 30 Sep 90 | 13 Jan 91 | 43 | 4 a.m.-8 p.m. |
| RUT | 1 Oct 89 | 13 Nov 89 | 15 | 5 a.m.-7 p.m. |
| MAR | 30 Sep 90 | 20 Jan 91 | 54 | 4 a.m.-8 p.m. |
| Ecuador | | | | |
| UNA | 3 Jun 90 | 26 Aug 90 | 38 | 4 a.m.-8 p.m. |
| PAN | 3 Jun 90 | 26 Aug 90 | 35 | 4 a.m.-8 p.m. |
| SAN | 3 Jun 90 | 26 Aug 90 | 47 | 4 a.m.-8 p.m. |
| TAN | 3 Jun 90 | 26 Aug 90 | 49 | 4 a.m.-8 p.m. |

# 3

# DEVELOPMENT OF DESIGN EQUATIONS

## 3.1 Long-Term Average Demand

The average use rate, also called the long-term average demand (LAD), is the average amount of water used by the community. It is typically expressed in gallons per hour (gph), gallons per day (gpd), or gallons per minute (gpm). The LAD is the average rate of water used in a community over the longest period for which data are available. It is the meter reading on the last day of record less the first meter reading divided by the time interval.

LAD values for the 16 communities in this study are shown in Table 3. Dividing the LAD in a community by the number of water users results in the long-term average per capita demand (LACD), with typical units being gallons per capita per day (gpcd). The LACD figures from Table 3 vary from 10 to 78 gpcd. The average for Guatemala is 24 gpcd, for Honduras 56 gpcd, and for Ecuador 51 gpcd.

The LAD is expected to increase with population; for example, a town with 1,000 people uses more water than one with 100. Although this general trend exists in the data, there are exceptions. The data in Table 3 are arranged by country in order of increasing population. The values in columns 5 and 6 indicate that the LAD generally increases as the population increases, but not always.

The fact that the LAD does not always increase with population and that per capita use rates are significantly different in Guatemala than in Honduras and Ecuador raises questions regarding the factors that explain the demand and the origin of the demand.

The LAD data from all 16 communities were pooled and regressed against population using ordinary least squares (OLS) analysis based on the apparent association in Table 3. The resulting equation in which LAD is in gph and POP = population is:[b]

$$LAD = -231 + 2.3\,(POP) \qquad (3.1)$$

where t(POP) = 7.1, N = 16, df = 14, and $R^2$ = 0.78. A graph of the regression is depicted in Figure 1. Equation 3.1 fits the data fairly well, with $R^2$ = 0.78, but the question remains as to whether other explanatory variable(s) also account for variation in LAD. Consequently, additional regressions were performed; these are described in the following paragraphs.

[b] In all the equations used in this chapter, LAD units are in gph unless noted otherwise. Numbers in the far right parentheses (in this instance 3.1), indicate the number of the equation, for text reference purposes.

**Table 3**

**Long-Term Average Demand Values**

| *Town* | *Population* | *Climate* | *LAD gph* | *LAD gpd* | *LACD gpcd* |
|---|---|---|---|---|---|
| Guatemala | | | | | |
| CAL | 348 | cold | 297 | 7,100 | 21 |
| CHU | 372 | cold | 425 | 10,200 | 27 |
| XET | 432 | cold | 174 | 4,200 | 10 |
| NUE | 804 | temperate | 1,179 | 28,300 | 35 |
| LACI | 840 | cold | 913 | 21,900 | 26 |
| Average | 559 | | | | 24 |
| Honduras | | | | | |
| BEL | 140 | hot | 454 | 10,900 | 78 |
| LACU | 260 | hot | 401 | 9,600 | 37 |
| COL | 350 | hot | 651 | 15,600 | 45 |
| BRI | 408 | hot | 932 | 22,400 | 55 |
| QUE | 819 | hot | 2,434 | 58,400 | 71 |
| RUT | 850 | hot | 2,157 | 51,800 | 61 |
| MAR | 960 | hot | 1,913 | 45,900 | 48 |
| Average | 541 | | | | 56 |
| Ecuador | | | | | |
| UNA | 245 | cold | 493 | 11,800 | 48 |
| PAN | 252 | cold | 446 | 10,700 | 43 |
| SAN | 820 | temperate | 2,031 | 48,800 | 59 |
| TAN | 1,243 | temperate | 2,804 | 67,300 | 54 |
| Average | 640 | | | | 51 |

The climate values in Table 3 indicate that the cold communities generally have lower per capita use rates than the temperate and hot communities. For this reason, a regression was performed with both population and climate as the explanatory variables of LAD. Climate is represented as a 0/1 dummy variable, where CLIM = 1 indicates a cold climate and CLIM = 0 indicates temperate or hot. The resulting regression equation and t-statistics show that both population and climate are statistically significant:

$$LAD = 144 + 2.0\ (POP) - 529\ (CLIM) \qquad (3.2)$$

where t(POP) = 6.8, t(CLIM) = 2.7, N = 16, df = 13, and $R^2$ = 0.86.

As noted earlier, the data in Table 3 indicate that the LACD per capita use rates in Guatemala are much lower than those in Honduras and Ecuador. Consequently, a regression was

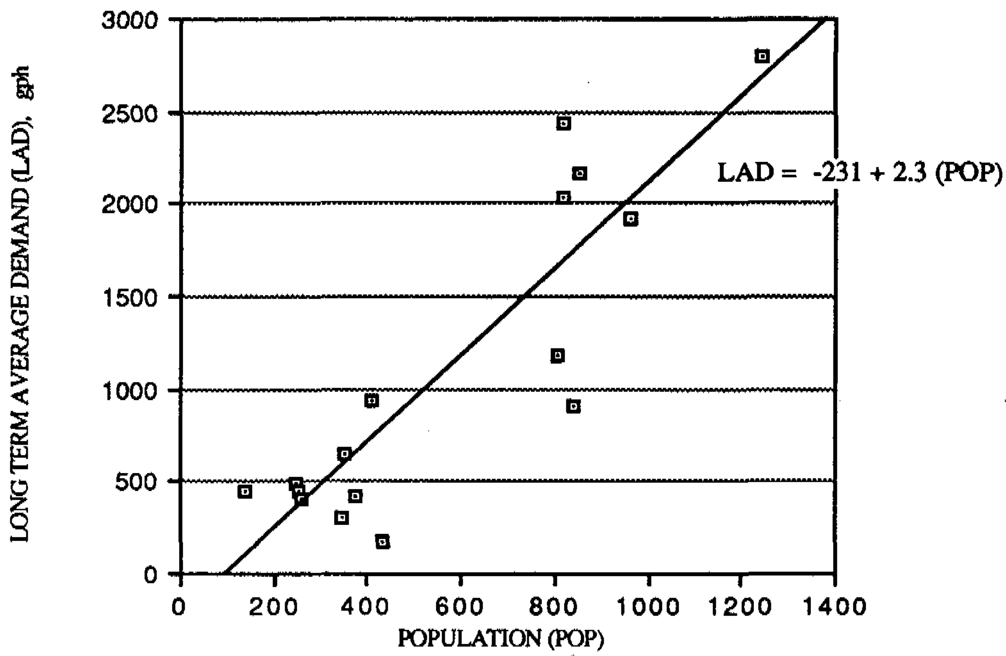


**Figure 1**

Long-Term Average Demand as
a Function of Population

performed with both population and country as the explanatory variables of LAD. The country designation is a 0/1 dummy variable, where CON=1 represents Guatemalan towns and CON=0 represents non-Guatemalan towns. In the resulting regression equation, both population and country are statistically significant:

$$LAD = 3.0 + 2.3\ (POP) - 699\ (CON) \qquad (3.3)$$

where t(POP) = 11.9, t(CON) = 5.3, N = 16, df = 13, and $R^2$ = 0.93. If climate is added to the model, it is not statistically significant. Hence, for this sample of only 16 towns, LAD appears to be due to population and country and not to climate. Therefore, for predicting LAD in gph for communities with different populations, the following two equations are used.

$$\text{Guatemala: } LAD = -318 + 1.6\ (POP) \qquad (3.4)$$

where t = 4.1, N = 5, df = 3, and $R^2$ = 0.85

$$\text{Ecuador and Honduras: } LAD = -66 + 2.4\ (POP) \qquad (3.5)$$

where t = 11.7, N = 11, df = 9, and $R^2$ = 0.94. Graphs of these equations are shown in Figures 2 and 3.

In Guatemala LAD Equation 3.4, the population coefficient is 1.6, implying an average daily use rate of 1.6 gph per capita, or 38 gpcd. For Honduras and Ecuador, the population coefficient from Equation 3.5 is 2.4, indicating average daily demand of 58 gpcd.

These equations may be useful predictors of demand, but they do little to explain it. Leakage, waste, or actual use might be the factors causing higher demands in the Honduran and Ecuadorian communities. To investigate this, average nighttime use rates between 8:00 p.m. and 4:00 a.m. were examined. A summary of the nighttime rates for each community is shown in Table 4.

For analyzing nighttime flow, one should consider the following. If the minimum flow in column 5 of Table 4 ever drops to zero or close to zero, the system is not leaking. Nighttime flow values are not specific to one moment in time but rather represent the average flow over an 8-hour period from 8 p.m. to 4 a.m.

If the minimum flow in column 5 is low but the maximum flow in column 6 is high, this would suggest that most nighttime flow is due to either waste or deliberate use. Indeed, a high standard deviation in nighttime flow indicates variation, which would not be the case if the flow were due only to leakage.

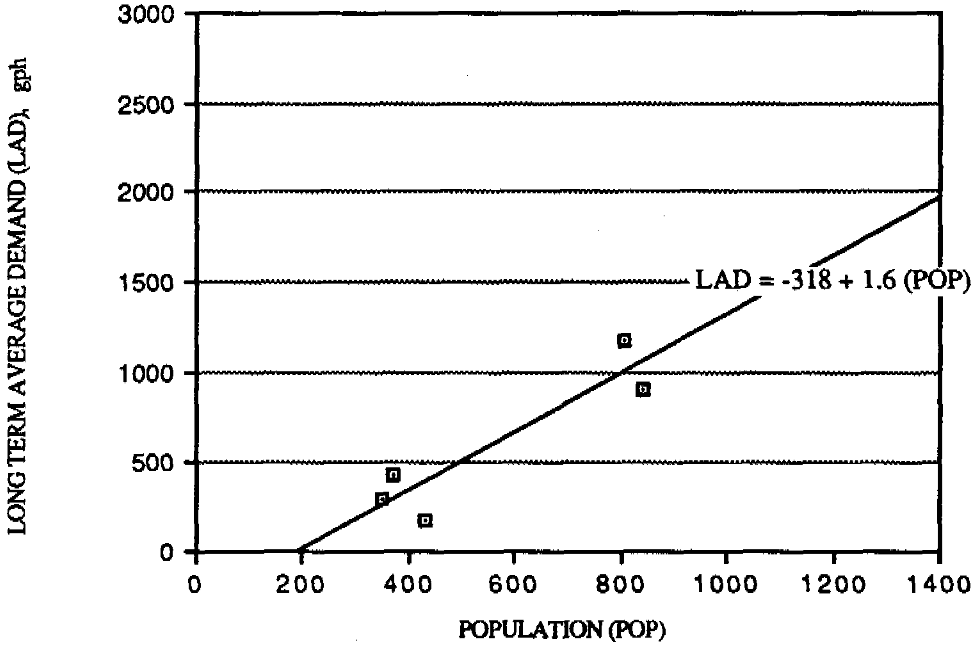


**Figure 2**

Long-Term Average Demand in Guatemala
As a Function of Population

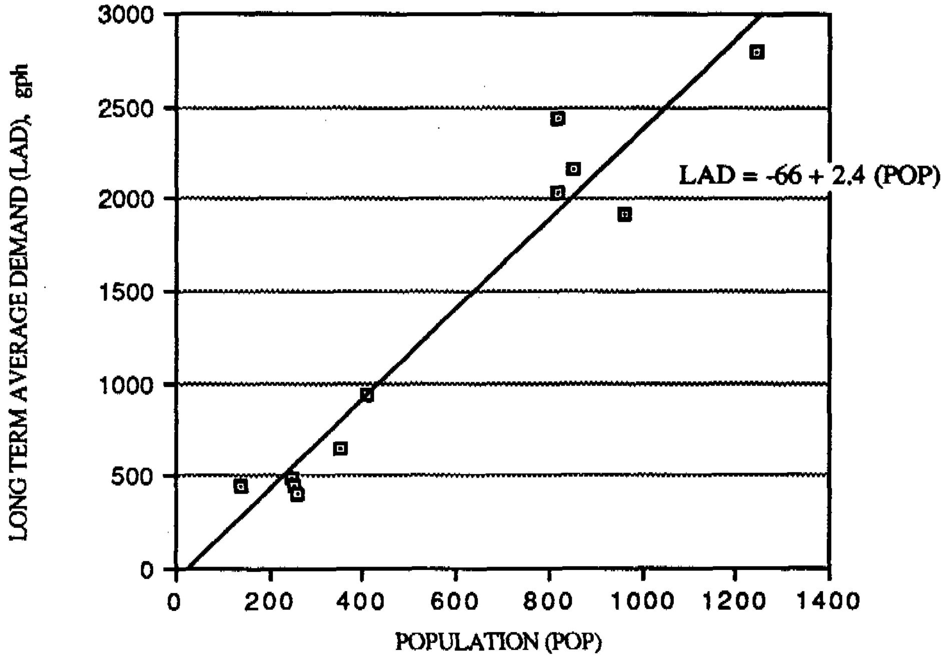


**Figure 3**

Long-Term Average Demand in Honduras and Ecuador
As a Function of Population

**Table 4**

Nighttime Use Rates

| *Town* | *LAD gpm* | *Average gpm* | *Standard Deviation* | *Minimum gpm* | *Maximum gpm* |
|---|---|---|---|---|---|
| Guatemala | | | | | |
| CAL | 5.0 | 0.4 | 0.6 | 0.0 | 2.8 |
| CHU | 7.1 | 3.6 | 0.5 | 3.2 | 6.0 |
| XET | 2.9 | 0.2 | 0.8 | 0.0 | 4.6 |
| NUE | 19.7 | 9.3 | — | — | — |
| LACI | 15.2 | 2.5 | 1.2 | 0.9 | 4.7 |
| Honduras | | | | | |
| BEL | 7.6 | 2.0 | 2.6 | 0.0 | 15.0 |
| LACU | 6.7 | 0.3 | 0.1 | 0.2 | 0.4 |
| COL | 10.9 | 1.7 | 0.8 | 0.8 | 3.9 |
| BRI | 15.5 | 10.9 | 2.6 | 7.1 | 14.4 |
| QUE | 40.6 | 36.0 | 11.4 | 0.1 | 56.9 |
| RUT | 36.0 | 24.0 | 2.6 | 18.4 | 27.6 |
| MAR | 31.9 | 11.5 | 4.6 | 1.1 | 25.3 |
| Ecuador | | | | | |
| UNA | 8.2 | 6.2 | 2.2 | 1.6 | 11.9 |
| PAN | 7.4 | 3.6 | 2.8 | 0.0 | 9.4 |
| SAN | 33.9 | 25.2 | 5.7 | 1.3 | 40.4 |
| TAN | 46.7 | 32.2 | 5.2 | 21.4 | 43.9 |

If the minimum flow in column 5 is high, it is unclear whether the system is leaking, whether the flow is due to waste, whether actual usage is occurring, or whether a combination of the three is indicated. However, even with high minimum nighttime flow, it seems logical to conclude that if the flow varies a great deal, and especially if the maximum nighttime flow in column 6 is considerably higher than the minimum in column 5, then at least part of the nighttime flow is due to waste or use.

If the minimum nighttime flow is high but the standard deviation is low, the cause could be leakage or waste from taps that are routinely left open.

The data for Guatemala in Table 4 show that three of the minimum nighttime flows in column 5 are close to zero. This suggests that these three systems do not leak. The relatively high maximum nighttime flows in column 6 suggest that periodic waste or use is taking place. However, in these three towns, the standard deviation is low, which indicates that deliberate nighttime use or waste is relatively minor. The data for CHU indicate otherwise. The nighttime flow rate in that town is about half that of average demand. The low standard deviation of this nighttime flow suggests that there may be a leak. The rate of nighttime use in CHU is roughly equivalent to one tap flowing fully open.

In both Honduras and Ecuador, the majority of the communities have small minimum nighttime flow rates and large maximum nighttime rates. This implies that these communities do not lose water through system leakage. Instead, some consumers probably leave their taps open overnight, either by neglecting to turn them off or by consciously deciding to use water at night. Possible exceptions to this occur in the towns of BRI and RUT in Honduras and TAN in Ecuador.

Except for 2 or 3 towns out of the 11 in Ecuador and Honduras, the evidence seems clear that high rates of demand are not due to leakage. On the contrary, the high demands are due to actual usage, which may include waste. It therefore follows that equations 3.4 and 3.5 can be used to predict long-term average household demand in the three countries studied.

## 3.2 Maximum Daily Peaking Factor

The ratio of demand on each day of meter readings to the long-term average daily demand for a community is called the daily peaking factor. With, say, 35 days of readings such as in PAN Ecuador (see Table 2), there are 35 peaking-factor values.

To select the maximum daily peaking factor (MDPF) for design purposes, a frequency analysis was made of the daily peaking factors for each town. The frequency distribution for one of the communities, PAN, is shown in Figure 4. For this research, the 80th percentile was arbitrarily selected for determining the MDPF. In the case of PAN, the resulting value is 1.2, which implies that on 80 percent of the days, the daily demand in the town was less than 1.2 times the long-term average demand. MDPF values for the other communities in the study are shown in column 4 of Table 5.

In industrialized countries, the MDPF has been found to vary with the amount of water demanded. The larger the community and the more water demanded, the smaller the MDPF. Consequently, the MDPF values in Table 5 were regressed against LAD, but average demand was not found to be statistically significant. The average MDPF for all 16 communities in the study is 1.2.

$$\text{MDPF} = 1.2 \qquad (3.6)$$

A graph of this regression is shown in Figure 5.

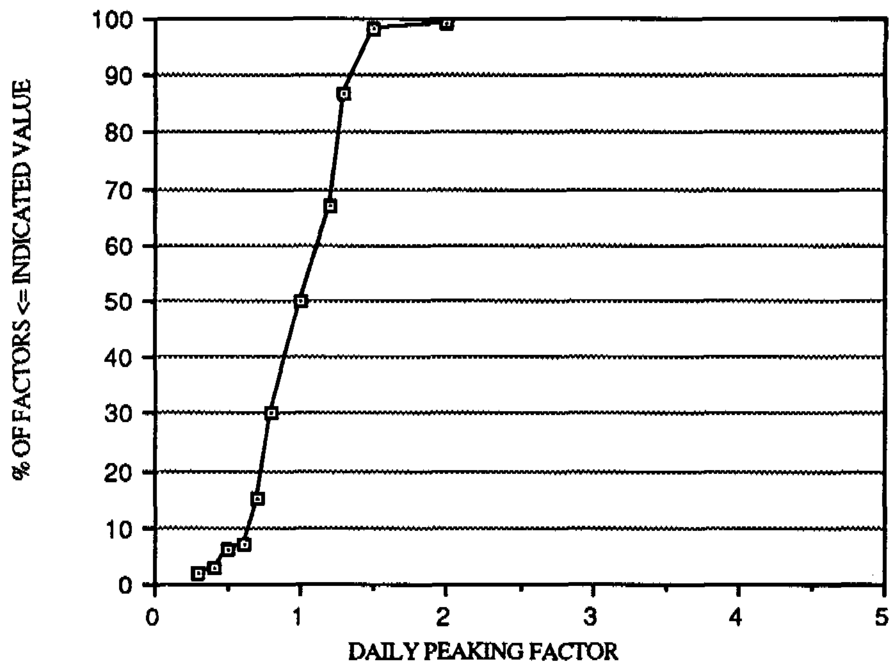


**Figure 4**

Distribution of Daily Peaking Factors for Panzaleo, Ecuador

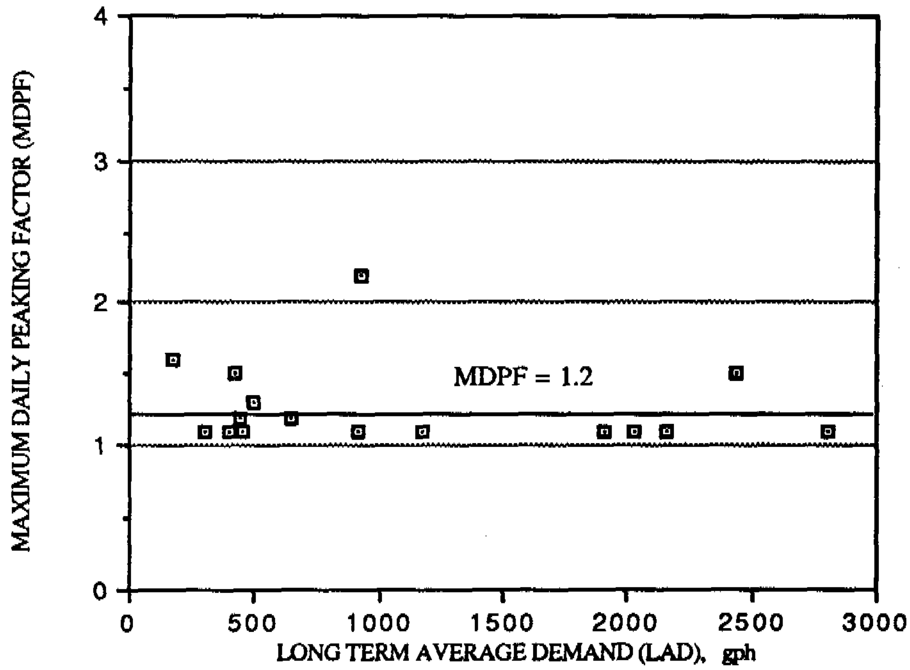


**Figure 5**

Maximum Daily Peaking Factor
vs. Long-Term Average Demand

**Table 5**

Maximum Daily and Hourly Peaking Factor Values

| *Town* | *Population* | *LAD gph* | *MDPF*[a] | *MHPF*[b] |
|---|---|---|---|---|
| Guatemala | | | | |
| CAL | 348 | 297 | 1.1 | 3.1 |
| CHU | 372 | 425 | 1.5 | 2.8 |
| XET | 432 | 174 | 1.6 | 4.5 |
| NUE | 804 | 1,179 | 1.1 | 2.7 |
| LACI | 840 | 913 | 1.1 | 3.5 |
| Honduras | | | | |
| BEL | 140 | 454 | 1.1 | 2.8 |
| LACU | 260 | 401 | 1.1 | 4.7 |
| COL | 350 | 651 | 1.2 | 3.3 |
| BRI | 408 | 932 | 2.2 | 2.7 |
| QUE | 819 | 2,434 | 1.5 | 2.1 |
| RUT | 850 | 2,157 | 1.1 | 1.9 |
| MAR | 960 | 1,913 | 1.1 | 2.6 |
| Ecuador | | | | |
| UNA | 245 | 493 | 1.3 | 2.4 |
| PAN | 252 | 446 | 1.2 | 2.5 |
| SAN | 820 | 2,031 | 1.1 | 1.5 |
| TAN | 1,243 | 2,804 | 1.1 | 1.9 |

[a] MDPF = maximum daily peaking factor
[b] MHPF = maximum hourly peaking factor

## 3.3 Maximum Hourly Peaking Factor

Figure 6 shows the hourly variation in water demand on June 4, 1990, for Panzaleo (PAN), Ecuador. Data on the diurnal variation in demand exist for all towns on all the days of meter readings. For the example in Figure 6, the maximum hourly rate of demand occurred at about 11 a.m. and was about 900 gph. The ratio of this peak hourly demand to the LAD is called the hourly peaking factor, which in this case was about 2.0 (from Table 3, LAD = 446 gph for PAN).

To determine the maximum hourly peaking factor (MHPF) in a town, a frequency analysis was made of all the hourly peaking factors for that town. The frequency distribution for PAN is shown in Figure 7. With MDPF, the 80th percentile was selected for determining the MHPF. In the case of PAN, the resulting value is 2.5, which implies that on 80 percent of the days, the maximum hourly demand was less than 2.5 times the long-term average demand. MHPF values for the other communities in this study are shown in column 5 of Table 5.

Just as larger communities are expected to have lower MDPF values, the same is true of the MHPF. Accordingly, the MHPF values for all 16 communities were pooled and regressed against LAD, which resulted in the following power function[3]

$$\text{MHPF} = 16.7\ (\text{LAD})^{-0.27} \qquad (3.7)$$

where LAD is in gph, t = 4.3, N = 16, df = 14, and $R^2 = 0.57$. A graph of this regression equation is shown in Figure 8.

## 3.4 Storage Tank Volume

The main purpose of a storage tank is to supplement inflow from the source in order to meet peak demands. A secondary purpose is to provide a reserve in the case of system breakdown, which was not considered in this study due to a lack of data on the frequency and duration of system failures. A storage tank fills when the rate of demand in the community is less than the rate of tank inflow, and it empties when the rate of demand exceeds the inflow rate. Required storage tank volume (STV) is the volume in gallons needed to meet the community's peak demand. The required STV in each community studied was determined using the hourly demand values for each day of meter readings. As one example, the hourly demands for Panzaleo on June 4, 1990, are shown in Figure 6 and tabulated in Table 6.

**Table 6**

Demand in Variation in Panzaleo, Ecuador, on June 4, 1990

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hour | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Demand in gph | 50 | 60 | 200 | 190 | 480 | 720 | 900 | 700 |
| Hour | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Demand in gph | 610 | 570 | 620 | 700 | 600 | 400 | 370 | 120 |

In this example, one can assume that water flows into the tank from the source of supply at a constant rate, say, 535 gph. At 5 a.m., the rate of inflow was 535 gph and the rate of outflow 50 gph. Hence, assuming the tank was not full, it would have filled at the rate of 535 - 50 = 485 gph. If the outflow rate of 50 gph at 5 a.m. remained constant until 6 a.m.,

[3] Equation 3.7 was derived by regressing log (MHPF) against log (LAD) using OLS and then taking the inverse log transform of the resulting equation.

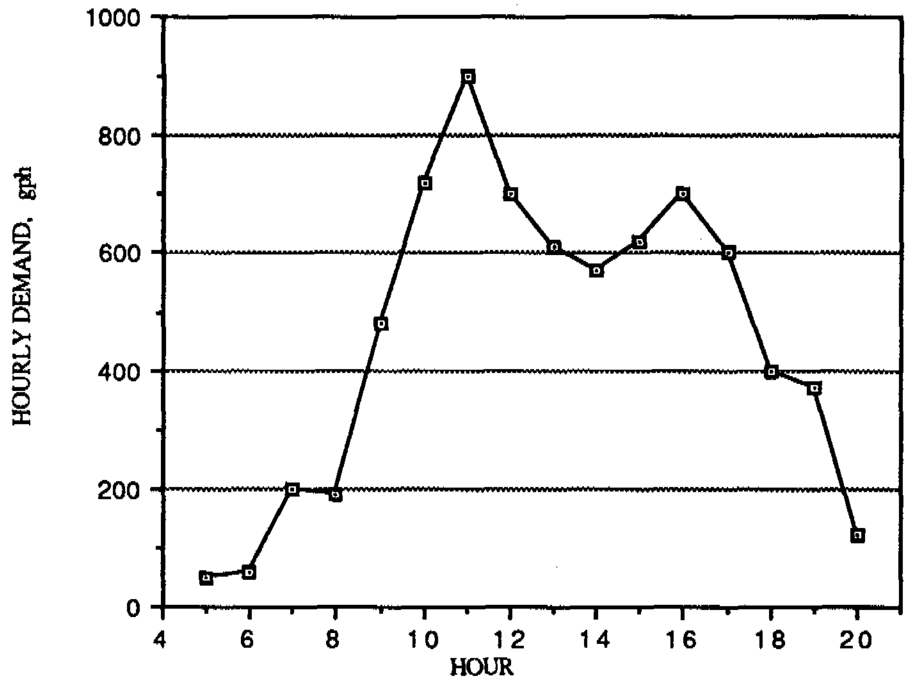


**Figure 6**

Demand Variation in Panzaleo,
Ecuador, on June 4, 1990

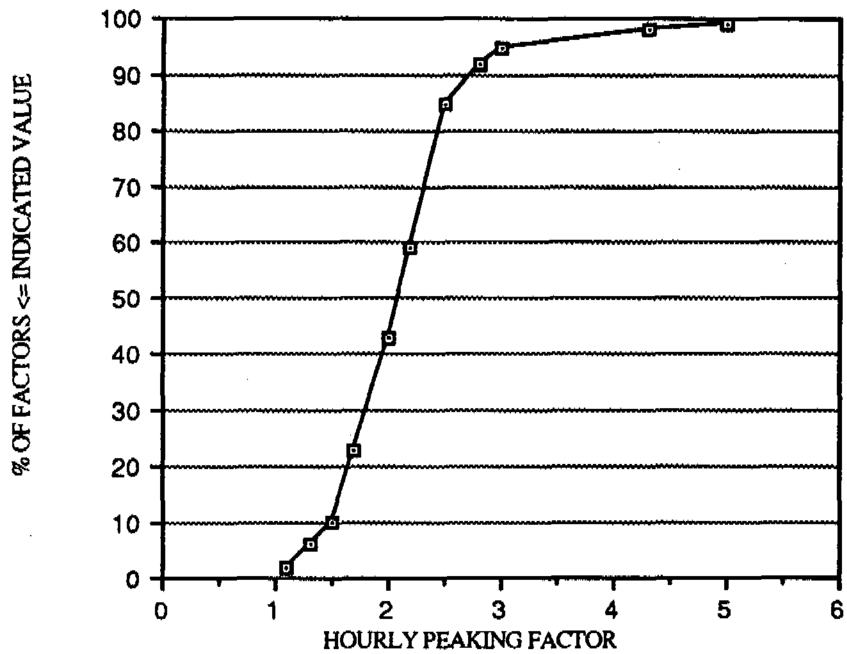


**Figure 7**

Distribution of Hourly Peaking Factors for Panzaleo, Ecuador

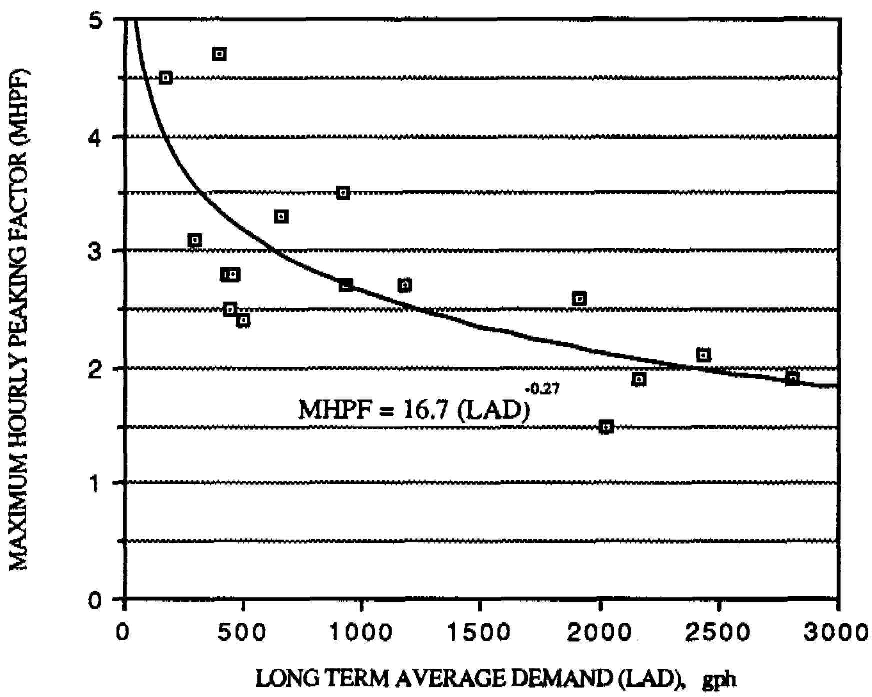


**Figure 8**

Maximum Hourly Peaking Factor
vs. Long-Term Average Demand

the volume of inflow to the tank in this period would have been 485 gal. At 6, 7, 8, and 9 a.m., the rate of inflow exceeded the outflow, causing the tank to fill. However, from 10 until 18 hours (10 a.m. and 6 p.m.), the outflow exceeded inflow, and hence the tank was empty. The amounts drained from the tank in each of the latter hours are the differences between inflow (535 gph) and the above demands:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hour | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Amount from tank in gal | 185 | 365 | 165 | 75 | 35 | 85 | 165 | 65 |

The required STV for this day of record is the sum of these amounts from the tank when it is draining, in this case, 1,140 gal.

Note that if inflow to the tank were at a different rate, a different STV would be required. For example, if the rate of inflow were 446 gph, which is the LAD for Panzaleo, the tank would drain from 9 to 18 hours and the total amount would be 1,886 gal. For determining STV values for the communities studied, three different inflows were assumed: the LAD for the community, 1.2 x LAD, and 1.4 x LAD.

A STV was obtained for each day of meter readings for each assumed rate of inflow to the tank. With three different inflow rates, the analysis produced three different required volumes for each day of record in each community. The required storage volume for a given inflow rate was determined in a method similar to that used in selecting peaking factor parameters. A frequency analysis of STV values was made for that inflow, and the volume at the 90th percentile was selected as the requirement.

A frequency distribution of STV values for PAN assuming an inflow of 446 gph is shown in Figure 9, and STV values for each of the study communities are shown in Table 7, where it is assumed that tank inflow is equal to 1.2 times the LAD for each town. Detention times in column 7 of Table 7 are equal to STV values in column 6 divided by LAD values in column 3.

For purposes of predicting STV in gal, a regression was performed using STV values for each day of meter readings in each community as a function of the maximum hourly outflow rate on that day (OUT, gph) and the assumed inflow rate (INF, gph). The logs of STV, OUT, and INF rather than the raw values themselves were used for the regression analysis, which was made using OLS. The resulting equation after taking the inverse log transform of the OLS equation is

$$STV = 0.37\ (OUT)^{2.32}(INF)^{-1.20} \qquad (3.8)$$

where t(OUT) = 8.2, t(INF) = 5.6, N = 48, df = 45, and $R^2$ = 0.70. Both explanatory variables are statistically significant. A graph of Equation 3.8 is shown in Figure 10 where it can be seen, for example, that if the inflow to a tank from its source of supply is, say, 1,000 gph and the outflow from the tank to meet peak hourly demand is, say, 2,000 gph, the required tank volume is approximately 3,000 gal.

### Table 7

Storage Volume and Detention Times

| *Town* | *Pop.* | *LAD gph* | *Tank Inflow[a] gph* | *MHPF* | *STV gal* | *Storage Tank Detention Time[b] hours* |
|---|---|---|---|---|---|---|
| Guatemala | | | | | | |
| CAL | 348 | 297 | 360 | 3.1 | 3,200 | 11 |
| CHU | 372 | 425 | 510 | 2.8 | 3,600 | 8 |
| XET | 432 | 174 | 210 | 4.5 | 3,200 | 18 |
| NUE | 804 | 1,179 | 1,420 | 2.7 | 7,000 | 6 |
| LACI | 840 | 913 | 1,100 | 3.5 | 9,500 | 10 |
| Honduras | | | | | | |
| BEL | 140 | 454 | 550 | 2.8 | 4,300 | 9 |
| LACU | 260 | 401 | 480 | 4.7 | 4,500 | 11 |
| COL | 350 | 651 | 780 | 3.3 | 8,000 | 12 |
| BRI | 408 | 932 | 1,120 | 2.7 | 9,500 | 10 |
| QUE | 819 | 2,434 | 2,920 | 2.1 | 18,500 | 8 |
| RUT | 850 | 2,157 | 2,590 | 1.9 | 7,500 | 3 |
| MAR | 960 | 1,913 | 2,300 | 2.6 | 14,900 | 8 |
| Ecuador | | | | | | |
| UNA | 245 | 493 | 590 | 2.4 | 2,300 | 5 |
| PAN | 252 | 446 | 540 | 2.5 | 2,100 | 5 |
| SAN | 820 | 2,031 | 2,440 | 1.5 | 3,600 | 2 |
| TAN | 1,243 | 2,804 | 3,370 | 1.9 | 9,500 | 3 |

[a] Inflow = 1.2 x LAD
[b] Detention = STV/LAD

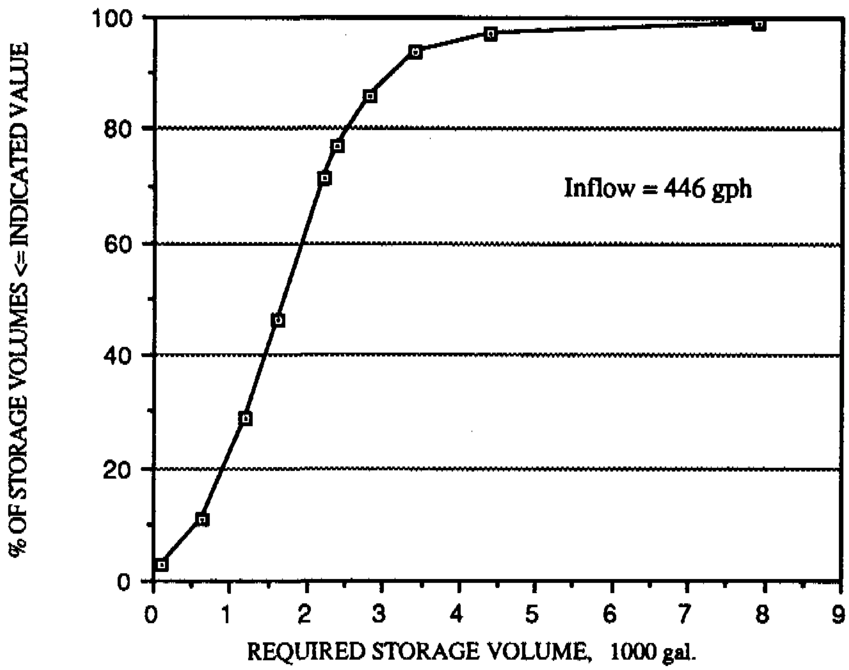


**Figure 9**

Distribution of Required Storage
Volumes for Panzaleo, Ecuador

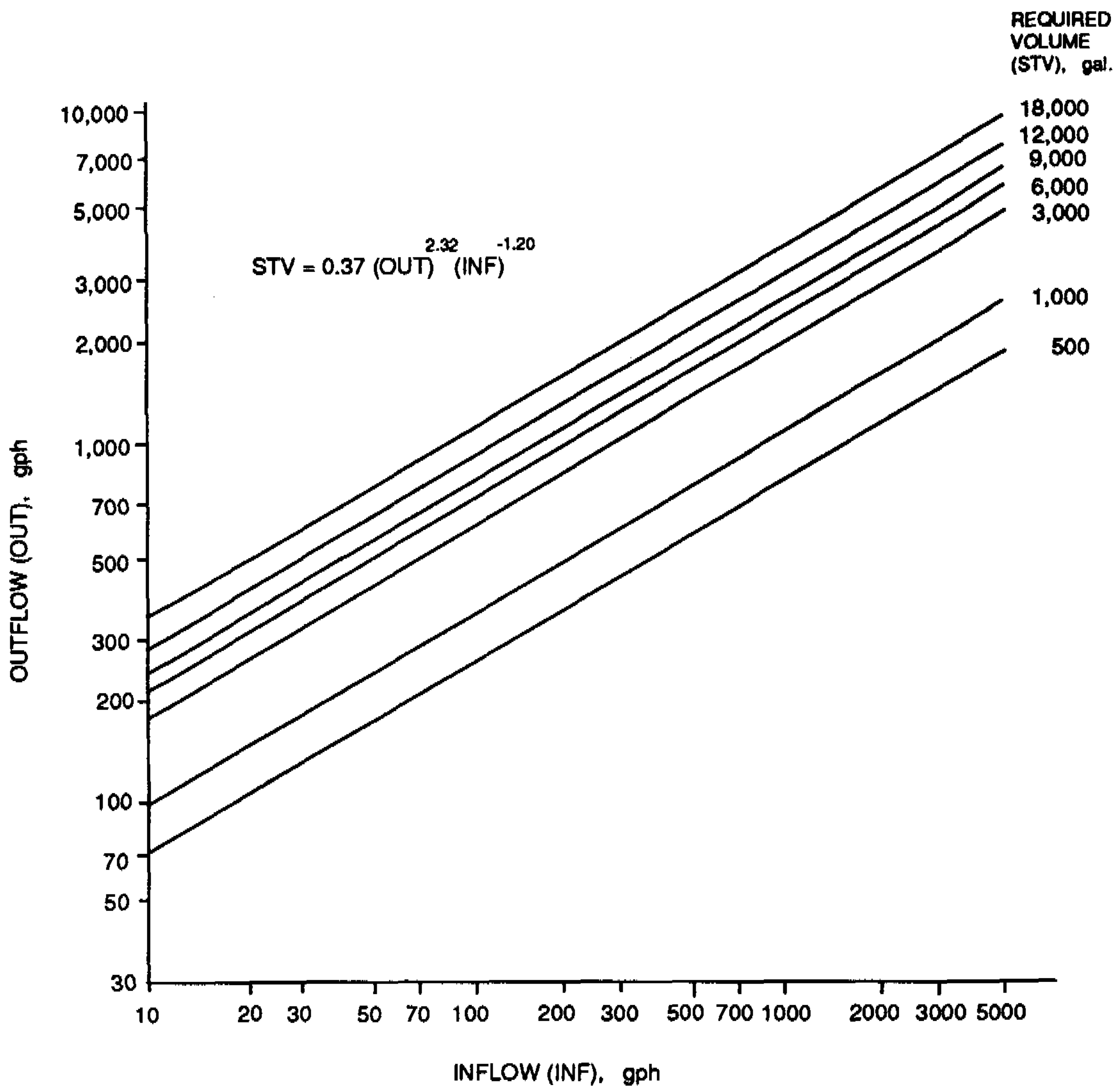


**Figure 10**

Required Storage Tank Volume as a Function of Inflow and Outflow

# 4

# USE OF EQUATIONS FOR DESIGN

Equations 3.4 through 3.8 provide a basis for estimating the flows and required capacities of water system components in communities of different size in Ecuador, Guatemala, and Honduras. Consequently, these equations effectively constitute a set of design standards. A key assumption in using them is that the 16 WS&S systems of this study are a representative sample of similar rural water systems in Ecuador, Guatemala, and Honduras, specifically ones that (1) are fed by gravity; (2) use individual yard taps; (3) charge a flat-rate tariff; and (4) restrict usage to household purposes only. Furthermore, use of these equations implies that the designers want systems to have sufficient capacity to meet the demands placed upon them and that the per capita demands measured during the study are representative of those that will exist throughout the design period.

## 4.1 Design Population

In determining a design population, the first task is to decide the future population for which the system should be designed, which was not considered in this study. In a town with a current population of approximately 600, one can assume the design population to be 900, which roughly corresponds to a population growth rate of 2 percent per year and a design period of 20 years.

## 4.2 Average Design Flow

If choosing a town in Guatemala, Equation 3.4 (LAD = -318 + 1.6 [pop]) can be used to predict the average demand (LAD) at the end of the design period. Substituting 900 for POP yields LAD = 1,100 gph. Dividing LAD by the design population of 900 yields an average per capita design flow of about 30 gpcd. If the town is in Ecuador or Honduras, the predicted average demand (LAD) at the end of the design period from Equation 3.5 (LAD = -66 + 2.4 [pop]) is about 2,100 gph, which is equivalent to an average per capita design flow of approximately 56 gpcd.

## 4.3 Source Capacity

Sources of supply are designed with sufficient capacity to meet the maximum daily design flow, which is the product of the maximum daily peaking factor (MDPF) and the average design flow. Equation 3.6 (MDPF = 1.2) shows that the MDPF was the same for all communities in this study. Hence, for a town with a design population of 900 in Guatemala, the source of supply should have a flow of at least 1,300 gph or 32,000 gpd. For a town in Ecuador or Honduras, the minimum source capacity is about 2,500 gph or 60,000 gpd. Recall that the MDPF was selected at the 80th percentile of the distribution of MDPF values. Hence, these design capacities imply inflows from sources that will meet daily demands on 80 percent of the days examined.

## 4.4 Transmission and Network Capacity

Transmission mains and piped distribution networks are designed with sufficient capacity to meet the maximum hourly design flow, which is the product of the maximum hourly peaking factor (MHPF) and the average design flow. Equation 3.7 ($MHPF = 16.7\ [LAD]^{-0.27}$) and Figure 8 show that MHPF depends on the average design flow LAD. The entire community normally lies downstream of a transmission main, and hence average design flow should be used for the value of LAD in calculating the peaking factor for the transmission main from Equation 3.7. For a town in Guatemala, the peaking factor for the transmission main based on the average design flow in Section 4.2 is about 2.5 ($= 16.7 \times 1{,}100^{-0.27}$). Multiplying the peaking factor by the average flow results in the peak hourly design flow for the main, which in this case is about 2,800 gph or 68,000 gpd. Similarly, the maximum hourly peaking factor for the transmission main for a town in Ecuador or Honduras from Equation 3.7 is about 2.1 ($= 16.7 \times 2{,}100^{-0.27}$), and the design flow is about 4,400 gph or 110,000 gpd.

Any one pipe in a distribution network usually does not serve the entire community but only those households located downstream from it. Hence, strictly speaking, different design flows with different peaking factors are needed for the different pipes of a network. Consider for example a pipe in the network of a Guatemalan town that serves 100. From Section 4.2, the average design flow is 30 gpcd, which implies that the average demand of the 100 people is 3,000 gpd or 125 gph. Substituting this value for LAD in Equation 3.7 results in a peaking factor for these 100 people of about 4.5 ($= 16.7 \times 125^{-0.27}$). Multiplying by the average demand of 3,000 gpd results in a design flow for the pipe that feeds the 100 people of about 13,500 gpd or 560 gph. Similarly, the design flow for any pipe in a network can be estimated using (1) the design population served by the pipe; (2) the average per capita design flow as obtained in Section 4.2; and (3) the maximum hourly peaking factor from Equation 3.7.

## 4.5 Storage Tank Volume

Equation 3.8 ($STV = 0.37\ [OUT]^{2.32}\ [INF]^{-1.20}$) can be used to estimate the required volume of a storage tank. From Section 4.4, the maximum hourly design flow to be met by the tank for a town in Guatemala is about 2,800 gph, which is the value to be substituted for OUT in Equation 3.8. The value for INF in Equation 3.8 is the design inflow to the tank from the source of supply. Assuming the source has the minimum required capacity (namely, the maximum daily design flow), the value for INF from Section 4.3 is 1,300 gph for the Guatemalan town. Substituting these values into Equation 3.8 (or using them in Figure 10) results in a required storage tank volume of approximately 6,500 gal. Similarly, the required tank volume for a town in Ecuador or Honduras is approximately 8,900 gal. Note that actual source capacity (which may differ from the maximum daily flow) should be used for the value of INF in estimating required tank volume.

## 4.6 Illustrative Results

The above examples use a town with a design population of 900 to illustrate application of the equations in Chapter 3. Table 8 shows similar results for towns with different populations in the three countries studied.

## Table 8

### Design Parameters and Capacities

| | *Design Population* | | | |
|---|---|---|---|---|
| | *300* | *600* | *900* | *1,200* |
| Guatemala | | | | |
| Average design flow (LAD), gph | 160 | 640 | 1,100 | 1,600 |
| Average design flow (LAD), gpd | 3,900 | 15,000 | 27,000 | 38,000 |
| Average per capita design flow (LACD), gpcd | 13 | 36 | 30 | 32 |
| Maximum daily peaking factor (MDPF) | 1.2 | 1.2 | 1.2 | 1.2 |
| Maximum daily design flow, gpd | 4,700 | 19,000 | 32,000 | 46,000 |
| Maximum hourly peaking factor (MHPF) | 4.2 | 2.9 | 2.5 | 2.3 |
| Maximum hourly design flow, gpd | 16,000 | 45,000 | 68,000 | 88,000 |
| Required storage tank volume, gal | 2,500 | 5,000 | 6,500 | 7,800 |
| Honduras and Ecuador | | | | |
| Average design flow (LAD), gph | 650 | 1,400 | 2,100 | 2,800 |
| Average design flow (LAD), gph | 16,000 | 33,000 | 50,000 | 68,000 |
| Average per capita design flow (LACD), gpcd | 52 | 55 | 56 | 56 |
| Maximum daily peaking factor (MDPF) | 1.2 | 1.2 | 1.2 | 1.2 |
| Maximum daily design flow, gpd | 19,000 | 40,000 | 60,000 | 81,000 |
| Maximum hourly peaking factor (MHPF) | 2.9 | 2.4 | 2.1 | 2.0 |
| Maximum hourly design flow, gpd | 46,000 | 78,000 | 110,000 | 130,000 |
| Required storage tank volume, gal | 5,000 | 7,200 | 8,900 | 10,000 |

# 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

1. This study shows that simple and relatively inexpensive data-collection efforts can yield a basis for rural water supply design standards and planning decisions that reflects actual local conditions.

2. The design standards derived in this study from water-use measurements pertain to certain types of systems (gravity-fed systems, with yard taps, flat-rate tariffs, and water-use restrictions). Using these standards for other types of systems or for similar systems with different management could be inappropriate. For example, if new water systems are to be designed to encourage rural dwellers to remain in their towns and not migrate to the cities, the systems' design flows and levels of service could be higher than those found in this study. Conversely, if increased cost recovery is an objective for new systems, with users paying fees that more nearly match costs, the flows found in this study may be too high for such design purposes.

3. The sample of communities studied was too small to make definitive statements about the effects on water use of such things as climate and socioeconomic conditions. Similarly, the periods of observation in the study communities were probably too short to capture entirely the daily and hourly variations of water use within systems. Nevertheless, the study provides a database that far exceeds existing knowledge about actual patterns of water demand in the types of systems studied.

4. Actual per capita demands, especially in Honduras and Ecuador, are significantly higher than the assumed flows that are being used for design purposes. This discrepancy highlights the urgency of examining current planning policies and standards, especially in light of the hundreds of millions of dollars being invested in rural water supply and sanitation.

## 5.2 Recommendations

1. Master meters should be installed in existing and new systems, and the meters employed in this study moved to other towns. Town officials should be taught how to read the meters and interpret the data, and use this information to improve system management.

2. Studies of the type described herein should be conducted routinely. Local universities, including students and professors in environmental engineering programs, should be engaged to assist in and/or direct these studies. In so doing, they will help develop new knowledge at the local level, enabling designers to depend less on foreign design standards and consultants. Local universities hold the greatest promise for disseminating this new knowledge and for having a positive impact on the practice of engineering. Financial assistance for conducting such studies, therefore, should be sought from A.I.D. and other donors.

3. Study communities should be selected based on different characteristics, such as levels of service, climate, socioeconomic characteristics, and tariffs, so that the effects of such factors, especially on per capita demand, can be studied systematically.

4. Within the study communities, the period of data collection should last about one year to ensure that seasonal effects are captured. Meter readings should be made every other week, as done in this study, and should include measurements taken throughout the night. Consideration should be given to using automatic meter recording equipment, although there may be some advantage to using meter readers, since such individuals will become familiar with the system in time and could prove to be a valuable resource to the study communities. Data should be analyzed immediately and not allowed to become "stale."

5. The findings from this study should be used to update current design standards. It would be premature to change the average per capita design flows; however, information from this study can be used for updating the design standards for sources of supply, transmission mains, distribution networks, and storage tanks.

6. Professional meetings should be held, preferably once a year or more often at first, to plan replication of this study in other communities and to discuss and compare findings. One outcome of such meetings should be to update design standards based on the findings. Within a few years, further updating may prove unnecessary and the meetings can then focus on other issues such as user demand, improved management, and cost recovery.

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