ABSTRACT

Piped water supply systems invariably lose water through undetected underground leakage. Not only is water being lost (often 10-15% of total water production in the U.S., and often over 40% in developing countries), but contaminated water may enter the system through the breaks.

In developing countries, in spite of the great need for delivery of more and cleaner water, leakage has not been addressed very often. This is due in part to the technical difficulty of detecting underground leakage in systems where there are very few records, where the pressure is often so low as to make sonic detection methods difficult, and where lack of sufficient valving makes it difficult to measure flows to isolated portions of the system. More significantly, leakage is part of a greater management problem that stems from lack of institutional support, skilled personnel, and sufficient funds. Because no guidelines exist for leakage control even where the institutional capacity is in place, however, this report focuses on the technical aspects of leakage control in existing small and medium-sized water systems in developing countries.

The report examines the causes of leakage, the methods of leak detection, leakage control policies practiced around the world, and finally gives suggestions for a simple procedure to establish priorities so that leakage control is carried out first where it will provide the greatest benefit per unit expenditure. Emphasis is placed on the need for an economic analysis of all leakage control programs.

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Unrepaired Leaks can be Costly

Water Loss in Gallons		
Leak this Size	Loss per Day	Loss per Month
●	120	3,600
●	360	10,800
●	693	20,790
●	1,200	36,000
●	1,920	57,600
●	3,096	92,880
●	4,296	128,980
●	6,640	199,200
●	6,984	200,520
●	8,424	252,720
●	9,888	296,640
●	11,324	339,720
●	12,720	381,600
●	14,952	448,560

From Heath Consultants, Inc.

1. INTRODUCTION

In recent years, water utilities in the United States have become increasingly aware of the importance of water conservation. One reason for this is the rising cost of water supplies. Energy costs and therefore pumping costs have risen; contamination of our water resources and a growing public concern over the health effects of industrial wastes have led to increased water treatment costs; and groundwater depletion has caused utilities to seek other, more costly, sources of water. At the same time, there is growing public resistance to construction of the impoundments often needed for extending service. Careful management of our water resources is emerging as a national priority. One important aspect of this is the reduction of water losses within water distribution systems.

Reduction of water losses is motivated by health concerns as well as economic issues. Underground leakage from pipes and valves is one of the major components of "lost water" in a system. Where treated water can escape, contaminated water can also enter the distribution system, creating the potential for outbreaks of waterborne diseases.

In Europe as well as the United States, leakage through broken or corroded pipes is an important issue. The problem may be more acute in Europe, given that European water systems are generally older than their American counterparts.

In developing countries, water losses are of far greater consequence than in the industrialized countries, both in terms of economics and the public health. In the industrialized nations, a reduction in water losses usually translates into a reduction in the amount of water treated and supplied, and therefore an immediate reduction in operating costs. If water demand is expected to grow over time, this reduction in apparent demand also means that future expansions can be postponed. In developing countries, on the other hand, where the demand for clean piped water far outstrips the supply, finding and repairing leaks in the system will make more water available to consumers. Rather than causing a decrease in the amount of water supplied, a reduction in water losses will usually lead to an increase in consumption, and therefore to an increase in revenues for the water utility. In addition, contamination of the water supply is a much more serious possibility in developing countries, where waterborne diseases are endemic, and where low water pressures within the distribution system make infiltration of contaminated water much more likely.

Reduction of water losses in developing countries, then, can extend water service to more people, improve the viability of water utilities, and decrease the possibility of contamination of the water supply. All of these are important elements in achieving the goal of "clean water for all" promoted by the United Nations through the International Drinking Water Supply and Sanitation Decade.

In spite of this, little effort has been expended on reducing water losses in developing countries, with the exception of some of the larger cities. There are a number of reasons for this apparent lack of concern: a shortage of resources; a lack of awareness of the problem; and a general lack of records on the distribution system that would make any attempt to track down pipes and valves extremely difficult.

The World Bank, which is the major funding agency for water supply projects in developing countries, is trying to draw attention to the important problem of water losses, and frequently makes reduction of these losses a condition of loans to utilities.

This report, then, addresses the important issue of water losses in developing countries, and offers some guidelines for a simple, rational approach to follow in reducing leakage. We first explain the concept of "unaccounted-for water" and describe its components; summarize the experience and policies of the water industry in the industrialized nations with unaccounted-for water, and then turn to the particular conditions in developing countries. We suggest a procedure to be followed by governmental agencies in developing countries in deciding which water systems would most benefit from a leakage control program, and how to estimate the economic benefits and costs of such programs. The same procedure is useful to the manager of a single system, who must decide in which parts of the system to carry out leakage control programs.

This report deals specifically with small- and medium-sized water systems. Large cities usually have the resources to hire consultants specializing in leakage control or water audits. Bangkok, Sao Paulo, Manila, Addis Ababa and other large cities have done just this.

This report also deals exclusively with existing systems. New water supply systems can profit from lessons learned in existing systems, and should be designed in such a way as to make it easier to keep records and monitor water use throughout the system. Most existing systems suffer from a variety of inter-related management problems that must be dealt with for water service to improve. Maps of tne distribution system should be developed, for instance, for leakage reduction efforts to be effective.

Table 1 gives figures for water losses in selected cities around the world, expressed as a percentage of total water production. There is no international agreement on the definition of unaccounted-for water (as is shown below), or on how to measure it, so the figures can not be rigorously compared from one study to the next. The table does give some idea of the magnitude of the problem, however. It is noteworthy that unaccounted for water is often 40 or 50% of the total supply in developing countries. It is also important to note the high percentage of water lost specifically through leakage. In all but one of the studies reporting figures for both unaccounted-for water and leakage, leakage accounts for the major portion of the unaccounted-for water.

2. CLARIFICATION OF TERMS

Unaccounted-for water is, literally, the water in a system that is not accounted for, often expressed as a percentage of the total water supplied from the treatment plant. There has been much confusion over the term, however, stemming from different definitions of what constitutes water actually "accounted for."

2.1 American definition of unaccounted-for water

In the United States, the Leak Detection Committee of the American Waterworks Association (AWWA) has suggested that unaccounted-for water be defined as the difference between the metered ratio and 100%. They define "metered ratio" as "the ratio of metered sales to metered delivery," that delivery measured presumably at the treatment plant. Referring to Figure 1, the metered ratio would then be the ratio of item 8 (metered sales) divided by the sum of items 4 through 11 (total delivery). The AWWA recommends the use of the term "metered ratio" because "unaccounted-for water" implies poor management and operation. They also specify that the metered ratio contain "no estimates or allowances for water losses such as meter error, unavoidable leakage, main breaks, public use for fire fighting, street washing, flat rates, etc." Although they state that "most systems will want to analyze the difference between their Metered Ratio and 100% by an auditing procedure that can account for the entire amount of water supplied to the distribution system," they suggest that when comparing performance with others, systems "should compare the Metered Ratio figure and not the Difference [i.e. unaccounted-for water] because the Difference contains estimates of various types." (Cole & Cole, 1980, pp. 1047, 1048)

The AWWA, then, considers as "accounted-for" only that water which is metered and paid for (item 8 in Figure 1).

2.2 British definition of unaccounted-for water

The British, on the other hand, define accounted-for water to include estimate legitimate consumption in unmetered areas. (In fact, British domestic use has historically all been unmetered.) The British National Water Council (NWC, 1980, Appendix A) defines "water unaccounted for" as "that water which is the difference between the total put into a supply and distribution system and the water accounted for." Unaccounted-for water is usually given by the formula "$U = S - (M + aP)$

where S = total water put into a supply system

M = total metered consumption

a = unmetered per capita consumption (estimated)

P = [unmetered] population served."

(Bays, 1984, p. 52)

Unaccounted-for water (U) can then be expressed as a percentage of the total supply (S).

Referring to Figure 1 and using the above formula, the percent of accounted-for water would be the sum of items 8 and 9 (total "known" consumption) divided by the sum of items 4 through 11.

In terms of the British definition, unaccounted-for water includes (Bays, 1984, p. 52):

"1) Leakage from mains, service reservoirs, overflows, etc.;
2) Commercial and industrial use not metered;
3) Incorrect estimate of domestic per capita usage when domestic premises are unmetered;
4) Inaccuracies of supply meters;
5) Inaccuracies of consumers' meters especially at low flows;
6) Water used for fire fighting, street flushing, building etc. which are [sic] not metered."

It is not clear from this whether public use (item 6 in Figure 1) would be included in the accounted-for volume if it were metered. Unmetered public use could be estimated, as could unmetered commercial/industrial use such as water used on construction sites (item 7 in Figure 1). In fact, the NWC recommends that the term "a" in the expression for unaccounted-for water include an allowance for unmetered commercial consumption. If public use and estimates for unmetered commercial/industrial use were included, accounted-for water would then be the sum of items 6 through 9.

2.3 Problems with the American and British definitions of the term

Neither the American nor the British definition seems entirely satisfactory. By the AWWA definition, New York City, which has no domestic meters, would have a metered ratio of 0 -- as would many systems in developing countries. And because the ratio is defined as "metered sales" divided by metered delivery, any public use of water, even if it were fully metered, would not enter into the metered ratio but would remain part of the "Difference," or unaccounted-for water.

The British definition seems more useful as an expression of how well the volume of supplied water is monitored, especially if that definition includes measures (meter-readings or estimates) of the public use of water, and estimates of unmetered commercial and industrial use. However, there are still several problems with this definition.

First of all, errors in the estimation of unmetered consumption (item 11 in Figure 1) could be over-estimation as well as under-estimation, so that water which is actually lost is mistakenly included in the accounted-for figure. In this case, the figure for unaccounted-for water would be smaller than it should be.

In addition, neither definition (British or American) specifies clearly where the "metered delivery" or total supply should be measured. If it were measured as it leaves the treatment plant (as shown in Figure 1), losses from any storage reservoirs or during transmission from the source would be ignored. Since that water has not been treated, however, the losses are of less economic significance than losses within the distribution system, and have less bearing on possible contamination of the water source.

A problem in measuring the total supply, which is not reflected in Figure 1 nor mentioned in the AWWA definition, is that large master meters may be faulty, in which case the figure used for total supply would be incorrect.

2.4 Other uses of the term "unaccounted for," and related terms

Most authors in the literature use the term "unaccounted for water" without any definition. In several cases, the term is used to mean only that amount unexplained after a detailed water audit. For example, Babcock (1984, p. 293) presents the results of a study carried out in Cambridge, Massachusetts, where reservoir leakage, underground leakage, and under-registration of meters were all measured or estimated. After including a term for "unavoidable leakage" as well, only 0.4% of the total supply remained unexplained, and this was labelled "unaccounted-for."

The city of Greensboro, North Carolina has developed a detailed accounting system of all water used in their system, similar to that used by Babcock, which includes estimates of "unavoidable leakage," meter under-registration, fire department use, street flushing operations, use within the treatment plant itself, and so on, leading to figures of accounted-for water that are near 100%. In fact, the figure for 1984 was 103.5% (Greensboro W&S form 262-2558, personal communication from municipal engineer Bill Finger, May 1985). This accounting system is useful for their internal operations, as they keep track of the separate line items; but the overall figure of 100% "accounted for water" doesn't lend itself to any useful comparisons with other systems. In fact, as more utilities carry out detailed audits, so that most of the water is in fact "accounted for" in a literal sense, whether it is lost to leakage or used productively, the term "unaccounted-for water" loses its usefulness.

As one example of other related terms in the literature: Courteau (1979, p. 31) uses the term "ratio of water sold to water produced" in describing work done in Libreville, Gabon, without specifying whether all the sales were metered.

2.5 <u>Use of the term "unaccounted-for water" in this report</u>

We do not have much occasion to use the term "unaccounted-for water" in this report, except when quoting the literature. When we do use the term for our own purposes, however, we use a modified version of the British definition, with accounted-for water defined as the sum of metered and estimated delivery to individual consumers (items 8 and 9 in Figure 1), and any measure or estimation of public and commercial/industrial use (items 6 and 7) that is available. Total water production is defined as the quantity leaving the treatment plant, where there is one. In those cases where there is no treatment, water production should be measured as it leaves the storage reservoir, well, or spring, as the case may be. If water is purchased from another utility, the total supply is the amount purchased.

The report does not actually discuss unaccounted-for water in great detail, but concentrates on the issue of actual losses in the distribution system.

2.6 Definition of "leakage"

One of the major components of unaccounted-for water is leakage. The National Water Council (NWC) defines "leakage" as "that part of waste which leaks or escapes or is lost other than by a deliberate or controllable action." "Waste" must first be defined, then; it is "that water which, having been obtained from a source and put into a supply and distribution system and into consumers' installations, leaks or is allowed to escape or is taken therefrom for no useful purpose." (NWC, 1980, Appendix A) Waste includes, therefore, accounted-for and paid-for water that is not serving a "useful purpose" -- taps left running in homes, excessive watering of lawns, etc. This is not something the water utility is directly responsible for, but is mentioned by the NWC because a campaign to encourage water conservation should be part of any water utility's strategy to preserve scarce resources.

This paper is mostly concerned with leakage. The term is used widely, with general acceptance of the definition given by the NWC. O'Day points out (1981, p. 259) that a distinction should be made between true leaks (at joints or valves) and breaks (fractures in pipes), in order to understand the causes of water loss and therefore the corrective measures that need to be taken. In fact, when leakage data are presented, they are often classified by type of leak (valve, pipe, hydrant, etc.). This classification serves the same purpose as making a distinction between breaks and "true leaks."

2.7 Definition of "water losses"

One final term of interest is "water losses," which is used loosely in this report to refer both to water lost through leakage and to water used illegally.

3. COMPONENTS OF UNACCOUNTED-FOR WATER, AND OTHER NON-CONSUMPTION WATER USE

The major components of unaccounted-for water, at least in industrialized countries, are leakage (item 4 in Figure 1), meter under-reading (item 10) and, to a lesser extent, illegal use of water (item 5). There are also some water losses between the source and the delivery point into the distribution system, which are not part of unaccounted-for water as we have defined it, but which merit some attention. We discuss the causes and importance of each of these components in turn, leaving the discussion of leakage to the last.

3.1 Meter under-reading

Domestic meters tend to register less than the actual amount of water flowing through them, for several reasons. For one, they wear with age; but even when in good condition, meters that rely on displacement of mechanical parts require some minimum flow to set the meter in motion, and therefore do not register very low flows.

It should be noted that meters may also over-register by registering air when no water is flowing. In the fully pressurized systems that are common in most industrialized countries, however, meter over-registration has not proved to be significant. In the four studies in Table 1 that report figures for meter under-registration, the figures vary from about 2% of the total water supply in Cambridge, Massachusetts, to about 22% of the water supply in nearby Boston.

In metered systems, meter under-reading can be a serious problem; unmetered water represents a direct loss of revenue to the utility. It is incorrect to assume, however, as is often implicitly done in studies of water use, that the volume of water unregistered by meters would all be transformed into revenues if the meters were repaired. There are several reasons for this. Meter under-reading often leads consumers to use excessive amounts of water; if charged for the full amount used, however, they may cut back on their consumption. Also, much of the water passing undetected through meters may be due to slow leaks on the customers' premises. When the meters are repaired or replaced so as to detect those low flows, customers do finally have the incentive to repair those leaks, thus lowering their apparent consumption. Records in Boston seem to confirm this; after a major remetering program begun there in 1977, water sales to customers have remained fairly constant, while the total volume of water purchased by the utility for distribution has decreased significantly. (Sullivan, 1981, p. 306).

Riomey (1982, p. 1027) argues that meter under-reading does not actually cause any revenue loss; over the long term, he claims, water prices adjust to cover true costs, so that with meter under-reading, the prices are higher. That may be the case in some systems, but water tariffs are not often set in accordance with the true costs of water production, nor are they adjusted very often, so the argument does not seem valid.

It should be noted in passing that measurement of meter error is actually more complex than recognized by most writers. It is not sufficient to test a representative sample of meters and find out by what percent they under-register. These tests should be carried out at a range of different flow rates, and the water use profile for that system should be determined (i.e., what percentage of consumption takes place at each flow rate) to get an accurate picture of the total volume passing unregistered through the meters.

In developing countries, most systems are either not metered, or are only partially metered. Many American authors advocate full metering and maintain that a system cannot be well managed unless all flows are measured. But full metering is not always a practical alternative. A study done by the World Bank and the World Health Organization in 25 developing countries showed that 67% of the water systems in those countries operate with intermittent pressure. (Shipman, 1978, p. R 23).

Intermittent pressure poses several problems for metering. Air is drawn through the meters when no water is available in the pipe, causing the meters to register the flow of air. Also, the surge caused within the pipe when pressure is restored can cause scale to sluff off the insides of the pipe and clog the meters. Finally, in systems with low pressure, the additional pressure loss caused by installing a meter may sharply reduce the flow of water reaching the house.

In addition to the technical obstacles to meter installation, there may be economic ones as well. Studies by the World Bank suggest that the benefits of having meters often do not justify the costs associated with meter installation and with meter reading and billing.

In many metered areas, "meter error" may be due as much to administrative problems with meter reading and billing as to defects in the meters themselves. Because of this, and because metering is neither widespread nor appropriate under the conditions of so many existing systems in developing countries, this paper does not deal with the problems of meter error, while acknowledging that it can be a serious problem in some areas. Quite a bit of research has been done on water use patterns in developing countries, proper sizing of meters, and appropriate maintenance and replacement policies (e.g. Hudson (1978), Newman (1982), Orr [1984]).

Although the discussion thus far (and the majority of the literature on meter error) has dealt with domestic meters, it should be mentioned again that master meters may be faulty as well. If they register less than the total flow, the volume of unaccounted-for water will appear to be smaller than it actually is. If, however, they err on the high side, the measure of total supply will be inflated and some of the volume considered as unaccounted-for will actually be non-existent water. In Addis Ababa, for instance, all three master meters were found to be over-reading, by as high as 32.5%. The unaccounted-for water was then shown to be only 22.0% of the total 1980/1981 supply, rather than the 30.3% that had been calculated with the faulty meters. This case seems somewhat unusual, but clearly, periodic calibration of the master meters is necessary.

3.2 Illegal water use

Illegal water use (item 5 in Figure 1) may take the form of tapping into an abandoned service line, dead end main, or hydrant, or bypassing a meter. In certain developing countries, illegal taps made directly into the distribution line are common, sometimes even equipped with a pump to withdraw more water, thereby lowering pressures in the distribution pipe. According to Estrada Echeverri (1983, p. 24), clandestine unmetered connections to urban water supply networks are widespread throughout Latin America, and are -- understandably -- most prevalent in slums and shanty areas.

Illegal use presumably varies greatly from one area to another. Only two studies in Table 1 give a figure for illegal use as a percentage of total water supply: 2-5% in Bangkok, and about 1.5% of total supply in Hong Kong. These are both large cities with fairly well-organized systems, and are certainly not representative of most systems in developing countries.

Because the measures taken to control illegal consumption are usually institutional measures rather than engineering ones, and because the water is actually being used productively, we do not deal with the issue of illegal water use in this paper.

3.3 Public water use

Public water use (item 6 in Figure 1) is often not metered or even estimated, and is therefore usually included in the volume of unaccounted-for water. This includes water used for firefighting, streetwashing or watering public parks, and also water used in public buildings. We suggest that it should also include any water used for routine maintenance of the water distribution system, such as the flushing of hydrants.

The AWWA suggests that a figure of no more than 1% of total production be used as an estimate of public water use, and this figure is generally used in the American literature

-- although Boston estimated its unmetered public use at 2.9% of total supply in 1978 and its firefighting flow at 1.3%, for a total of 4.2% of the supply going to public use. (Sullivan, 1981, p. 305)

In developing countries, the figures for public water use may be quite different. Fire flow is usually lower than in the industrialized countries; but on the other hand, the government is often the largest employer, especially in the cities, which means that public water use may be relatively much larger than in the industrialized nations. The amount of public use should be estimated, but given that it is a legitimate and productive use of water, it requires no corrective action, unless it were to encourage a more modest consumption.

3.4 Losses from service reservoirs

Losses from service reservoirs in the distribution system are actually a component of total distribution losses (item 4 in Figure 1). In a survey of 81 towns in 15 industrialized countries, Reed (1980, p. 0178) reports that 3% of all leakage (which would be a smaller percentage of total water supply) came from service reservoirs. Because the service reservoirs within any system are generally visible, accessible, and few in number, controlling losses from service reservoirs is usually more straightforward than controlling leakage from underground pipes, and is therefore not discussed in this paper.

3.5 Other losses or water uses

If total water production is measured as the output from the treatment plant, any water losses occurring before that point do not enter into the calculations of unaccounted-for water, but they do deserve at least brief mention here.

A certain amount of water is used in treatment plants for regular operations: backwashing filters, desludging clarifiers, etc. (item 3 in Figure 1). This amount could be reduced somewhat by using different technologies (for instance, using a combined air and water backwash). Use in treatment plants should not be considered as a loss, but rather as another legitimate non-revenue use.

Open reservoirs inevitably lose enormous quantities of water through evaporation, which is taken into account during design; but they may also lose a considerable amount through overflow due to malfunctioning level valves, pumps that don't shut off, etc. (item 2 in Figure 1).

If the water source is far from the population to be served, transmission mains are needed to deliver the water to the treatment plant, and these mains may develop leaks (item 1 in Figure 1).

3.6 Underground leakage

Losses in the distribution system are due to leaks in service reservoirs (discussed earlier), hydrants, valves, joints, and the pipes themselves. Hydrant leaks and valve leaks are due either to improper closing or operation, or to structural defects. Leaks in joints or pipes (the latter being what O'Day refers to as "breaks") are the most difficult to find, and are responsible for the greater part of water lost to leakage.

Pipe leaks are caused by a variety of interacting factors. O'Day and Staeheli (1983, pp. 1 & 2) give a good explanation: "Mains can be viewed as structures which are stressed by both internal and external forces. As long as a main's strength exceeds the stresses caused by these forces, the main will give reliable, break-free service. If these forces exceed the main's strength, however, it will fail as a structure, which will result in a main break." Either increased forces or decreased strength, then, contribute to main breaks.

3.6.1 Loss of pipe strength

The strength of a pipe depends on the properties of the material of which it is made, how it is made, and the wall thickness. Loss of strength in metal pipes is caused by corrosion, which reduces the pipe wall thickness by attacking either the internal or external walls of the pipe.

One process leading to internal corrosion is cavitation, in which water flowing at a high velocity becomes turbulent and is therefore subject to rapid changes of pressure. Dissolved bubbles of gas are released and then redissolved, and the repeated collapse of these bubbles against the pipe wall erodes the surface, causing pitting. This type of corrosion occurs at points where high velocity flow causes sudden low pressures, for instance at bends in pipes, and the only preventive measure is to avoid high velocity turbulent flow.

The second and more widespread cause of corrosion is the electrochemical reaction caused by the proximity of dissimiliar metals with a difference in electric potential. Water acts as the electrolyte and an electric cell is created, in which the metal functioning as the anode is gradually eaten away. A single metal such as iron can also corrode in the presence of water -- parts of the surface act as anodes, other parts as cathodes. This electrochemical corrosion can occur either internally or externally. There are a number of corrective measures that can be taken. To control internal corrosion, the water quality can be controlled (for pH, CO_2 content, alkalinity) and the pipe walls can be lined. To control external corrosion, backfill is laid around the pipe to facilitate drainage, and "sacrificial anodes" can be attached to the pipe -- small pieces of metal that will be attacked by corrosion before the pipe surface itself is affected.

Because corrosion is a continuous process, its effects are cumulative. To quote O'Day and Staeheli again, "The progressive effect of corrosion on water main condition has come to be equated with deterioration due to the passage of time" (O'Day & Staeheli, 1983, p. 3). The gradual weakening due to corrosion explains why older pipes often have more leaks than newer ones of the same type in a given area or system. But because there are so many other factors that affect pipe failure, and because corrosion proceeds at such different rates in different settings, age alone is not a good predictor of leakage rates in distribution systems.

It is important to note that a large portion of the water pipes laid in developing countries are made of asbestos-cement or plastic, neither of which is affected by this electrochemical corrosion. So while corrosion contributes greatly to leakage in industrialized countries by destroying the structural integrity of the mains, that cannot be the case for most of the distribution systems considered here. Plastic pipe loses its strength when exposed to the sun for too long; material in asbestos-cement pipes can be lost when the water is aggressive; and all types of pipe in developing countries may have low strength due to poor manufactured quality.

3.6.2 Categories of factors affecting leakage

Shamir and Howard (1979, p. 248) classify the factors affecting leakage into four categories (see Figure 2): the pipe itself, the environment in which it is laid, the quality of work during construction, and the service conditions.

The first category in Figure 2, those factors related to the pipe itself, are the factors that determine the initial strength of the pipe. Included here are the type of material (cast iron, PVC, cement, etc.), the quality of that material (stemming from the process by which it was manufactured), the diameter and the wall thickness.

The second category is made up of those factors related to the environment. Of those, the first four contribute to leakage by causing corrosion and decreasing the wall thickness and therefore the strength of metal pipes. The first three (soil composition and moisture, and water quality) were discussed earlier; the fourth, the presence of electric trolleys, can lead to stray DC currents in the soil that strike the pipe and cause extensive localized corrosion. If continued unchecked, corrosion eventually leads to holes in the pipe wall.

The remainder of the environmental factors cause stresses in the pipes. Loading from overhead traffic and frost penetration cause soil movement and create lateral and vertical forces on the pipe. These forces may cause ring cracks (around the circumference of the pipe) or longitudinal cracks (O'Day & Staeheli, 1983, p. 4). There are also one-time natural occurrences, such as earthquakes, that may severely damage pipe. For instance, the water supply network in Tokyo suffered extensive damage in the Great Kanto Earthquake in 1923. (Sugawara, 1983, p. 1)

The third category of factors affecting leakage in Figure 2 is the quality of the work during construction:

placement of pipes, construction of joints, and especially compaction and levelling of the bed. If the bed is uneven, the pipe is not supported uniformly along its length, and is more susceptible to damage through loading.

Quality of construction is much harder to quantify than the other factors, but may well be one of the most important factors affecting leakage. This is especially true in developing countries, where lack of experience, standards and quality control means that many systems are not constructed as carefully as they could be.

The last category in Figure 2 is made up of operational variables, that can often be changed without major structural changes. Water pressure throughout the system and water hammer at dead end mains are internal forces that can cause rupture or a blow-out. These can usually be avoided by opening and closing valves slowly. High water velocities, as mentioned above, can cause cavitation and pitting.

The last item in this last category, maintenance policies, is somewhat different from the others in that it can alter the effect of the environmental and service condition factors. For instance, some utilities periodically clean and line their pipes, which prevents internal corrosion. Others install anodes on the exterior pipe surface each time they have to repair a metal pipe, thus preventing further external corrosion. And because undetected leakage can cause further leakage by eroding the bedding along the pipe length and causing stress points, utilities that make a point of carefully closing all hydrants after use will not only have fewer hydrant leaks, they will also prevent other leaks. And of course any utility that has a leakage control program will cut down on the overall level of leakage.

3.6.3 Leakage data

Table 2 presents data from several different leakage studies, all but one in the U.S. The most common classification of leakage is in terms of where the leaks occur in the distribution system -- hydrants, valves, mains, joints, service connections. Two studies (Moyer, 1982, and Curtiss, 1983) also distinguish between leaks on the customer's portion of the service connection and leaks on the portion of service connection that is under the utility's jurisdiction. Presumably the same physical factors would be at work in these two cases, but the distinction is relevant in terms of who is responsible for repair of those leaks, and also in terms of the dollar value of the water lost (leaks on the customer's premises do not represent a loss of revenue to the utility, unless they are at such low flows that they escape registration by the meter).

Where the original articles did not give their results in the form shown in Table 2, we have calculated the figures presented here from their data. We have also converted all results reported in British units into metric units.

Data for numbers of leaks are much more precise than those for volume, because leakage volume is usually only estimated, either during the detection phase according to the intensity of the leak sound, or by visual inspection during repair. The flow rates reported are generally in round numbers -- for instance, 1/2 l/min, 1 l/min, 5 l/min, 10 l/min, etc.

3.6.3.1 Problems with the data

Table 2 provides an indication of the information on leakage frequencies that is available in the literature, and of where leakage is occurring in systems that have been studied. There are a number of problems:

a) One author (Sullivan, 1981) explicitly includes joint leaks with the figures for main breaks, whereas the others do not specify whether joint leaks are included.

b) These results are all from actual leakage detection efforts, but in most cases the methods are not specified. As is explained in the next section, a number of different leakage detection methods exist. The method used, and also the general maintenance policies in effect before the leak detection survey, have a bearing on the amount of leakage uncovered and where it is found.

c) The distribution of leaks among the components of the system are dependent on the system characteristics shown in

Figure 2. If corrosion is an important factor, one would expect relatively more leaks in the pipes themselves (in a system with metal pipes). If there are large temperature variations, one would expect more joint leaks. And if there is little control over hydrant usage, one would expect more hydrant leaks than in other systems.

d) The distribution of leaks among the components is also necessarily dependent upon the composition of the network -- the number of hydrants, valves and service connections per kilometer of main, and the average length of service connection. In very few cases in the literature is the composition of the network given. If the networks in Table 2 are significantly different, comparisons among the systems are meaningless.

One might expect the U.S. distribution networks to be fairly similar -- or at least more similar to each other than they are to the water system in Barranquilla, Colombia shown in the last column of Table 2. Hudson (1978, p. 364) quotes the assumption made by Kuichling "that on the average there are 504 pipe joints, 12 hydrants, 10 stop valves and 100 service pipes per mile of distribution pipe," when Kuichling was developing a figure for the "average undiscoverable leakage in a well-constructed distribution system" around the turn of the century. The figure reached by Kuichling (based on an assumption of a certain number of drops per second leaking from each joint, hydrant, stop valve and service connection) was 2500 to 3000 gallons per day per mile of distribution pipe, or about 6 to 7 cubic meters per day per kilometer. This figure for unavoidable leakage is used throughout the American literature, but Babcock is the only author who explicitly acknowledges that the figure is based on the assumption of "504 pipe joints, 12 fire hydrants, and 100 service connections per mile," and states that "This assumption was verified by comparison against the City's [Boston's] existing distribution system." (Babcock, 1984, p. 296) No such figures were available for the studies presented here.

e) Some of the studies shown here are for entire cities or distribution systems (Mamaroneck, Barranquilla), whereas others are for "pilot zones" which may not be representative of the entire system. For instance, the results reported for Long Island are for the first 20 miles surveyed. The report on this survey states that when they surveyed the remaining 60-plus miles of the distribution system, "the results of this second segment were not quite as impressive as the first" -- although still very worthwhile. (Marchon, 1985, p. 1) The average rate of 174 m^3/day per leak in this first survey, much higher than the average rates in other studies, stemmed from two very large main leaks on main roads, which were dumping directly into storm and sewer manholes and had therefore not surfaced.

3.6.3.2 Conclusions from the data

In spite of these limitations, several conclusions can be drawn from Table 2:

a) In all cases, when leaks occur in mains, they make up a fairly small percentage of the total number of leaks, but a much larger percentage of the total leakage volume. To take but one example, leaks in mains and joints made up only 7.2% of the total number of breaks in the Boston study, but were responsible for 23.6% of the leakage volume uncovered.

b) Hydrant leaks, which accounted for anywhere from 15 to 81% of all leaks in the U.S. studies cited here, made up a much smaller proportion of the volume lost. For instance, in the same Boston study, 34.1% of all leaks found were in hydrants, whereas only 3.6% of the volume lost was due to hydrant leaks. In fact, when Moyer et al. (1982) analyzed the costs and benefits of the leakage detection and repair effort in Mamaroneck for each category of leak, they came up with a negative net benefit for hydrant repair -- the costs of detection and repair were greater than the value of the water saved (calculated as the sum of the wholesale purchase price and the chemical and power costs). But it does not necessarily follow that one should ignore the hydrants and look for main leaks first. Because hydrants are the most accessible points on the distribution system, they are the easiest points to check, and as is explained in the next chapter, main leaks are usually located by listening at the hydrants for the characteristic leak sound.

c) There can be wide variations in leakage rates within one system (which is an important point we shall come back to when developing a leakage control policy). The three zones in the Schenectady survey were chosen specifically to evaluate the effects of pipe age (Low Zone), sandy soils (Bellevue) and a high groundwater table (Woodlawn). (Lilley, 1984, p. 2) And, in fact, the three zones had different leakage patterns. The zones were small enough that no main breaks were found in two of them (Low Zone and Bellevue). Although main breaks are usually the largest type of leak and are responsible for raising the average leakage rate per leak, one of the zones with no main breaks, Low Zone, had a higher average leak rate per leak (84.4 m3/day) than did Woodlawn, the zone with two main breaks, which had a 72.9 m^3/day average rate per leak. The Low Zone also had a much higher number of leaks per kilometer than either of the other two zones (1.7 leaks/km for the Low Zone, .94 leaks/km for Bellevue, and .43 leaks/km for Woodlawn). And although Bellevue had a lower average leakage rate (41.2 m^3/day per leak) than did Woodlawn at 72.9 m^3/day/leak, the higher density of leaks per km in Bellevue meant that it had a slightly higher volume of water lost per km of main (38.6 m^3/day) than did Woodlawn (31.4 m^3/day/km).

In conclusion, then, although this type of data cannot be rigorously compared from one system to the next, it is useful for looking at trends and especially for comparing zones within a single system, which are presumably subject to the same maintenance policies and the same reporting procedures.

The number of leaks is relevant in terms of the cost of detection and repair, and the volume of leakage determines the benefits from water saved. This type of data (number and volume of leaks by type, kilometers surveyed, and also type of pipe) should be collected for any leak detection survey.

4. METHODS OF LEAK DETECTION

4.1 Leakage control and leak detection

A distinction must be made between "leakage control" and "leak detection." Leakage control means any program designed to reduce the leakage in a system or keep it at a low level, usually through monitoring of flow levels in different districts or regular "sounding" throughout the system. Leak detection, on the other hand, refers to the process of locating the leak. All leakage control programs include some form of leakage detection to pinpoint the leaks which have been discovered or are suspected.

Detection of underground leaks is usually based on detecting the sound made by water escaping through the leak, and depends on that sound being transmitted either along the pipe to a convenient listening point such as a hydrant or valve box, or through the earth to the ground surface above the pipe.

4.2 Leak sound

A leak produces several different sounds, at different frequencies. One type of sound wave is created by the vibration of the pipe at the orifice and is transmitted along the pipe wall. This sound is usually at a frequency of about 500 - 800 Herz, according to Heim (1979, p. 67);

the British NWC gives it a range of .3 - 1 KHz (NWC, 1980, p. 120). This sound can be heard by what the British call "direct sounding" -- listening at a hydrant, valve box, corporation stop, or other point in direct contact with the pipe. (See Figure 3, "direct sounding at a hydrant.")

Another type of sound is produced at a lower frequency, about 100-250 Herz according to the NWC (1980, p. 120) or anywhere from 20 to 250 Herz according to Heim (1979, p.67). There are actually two different phenomena producing sound at this frequency. One is the impact of water against the soil around the leak, and the other is circulation of water in a cavity in the soil near the leak, which produces a sound like that of a fountain (Heim, 1979, p. 67). These sounds are transmitted through the soil and can be heard at the surface above the leak; listening for these is called "indirect sounding" or "surface sounding" by the NWC. (See Figure 3, "indirect sounding.") Whereas the first, higher-frequency, sound can travel along the pipeline for long distances, the second sound is localized around the leak. Listening for this sound on the surface, then (indirect sounding), is very important in pinpointing the exact location of a leak for excavation.

4.3 <u>Sounding equipment</u>

The original and most basic instrument used to listen for leaks is the sounding rod or "listening stick," which is a wooden or metallic stick that mechanically transfers the leak sound to the human ear. These rods can be used for either direct or indirect sounding. The NWC refers to all such rods as stethoscopes.

Although the British generally use the same stethoscopes for both categories of leak sound, it is much more common in the U.S. to have two different instruments, adapted to the two types of sounding. The "aquaphone" is a metal spike with what resembles an old-fashioned telephone receiver on the listener's end, and is used for direct sounding, in contact with some element of the distribution system. The "geophone" is used for indirect sounding on the ground, and has a diaphragm on the end, like a doctor's stethoscope. It can also have two diaphragms to give the listener a stereo effect. (Cole, 1980a, p. 3)

Sounding can also be done with electronic instruments that amplify the sound and incorporate frequency filters to remove some of the extraneous noise. The signal from the amplifier is usually directed both to headphones and to an indicating meter. Using frequency filters, instruments have been developed that are specific to the two different frequency ranges that occur in leak sounds. The indicating meter provides an objective scale of sound intensity that helps the operator compare different leak sounds.

Figure 3 shows an electronic aquaphone with the probe touching a hydrant, and an electronic geophone set on the ground. With a leak located as shown in the figure, the aquaphone should give a higher reading (higher intensity of sound) at hydrant A than at hydrant B, because hydrant A is closer to the leak. Similarly, the geophone should register its highest reading when set directly over the leak (at point C) than a few meters away (point D). There are a few cases in which these general rules do not apply; those cases are discussed below.

The aquaphone and geophone, used as shown in Figure 3, are the most common sounding instruments; however, there are several other sounding techniques which also rely on locating the point of maximum sound intensity. Figure 4a snows a metal probe inserted into the ground to touch the main itself. This is oone when the above-ground access points are too far apart, or when the conventional method of direct sounding fails to detect a leak sound in a section of main that is suspected to have a leak.

Figure 4b shows a hydrophone, a more sensitive probe which is immersed directly in the water, usually through a gate valve or hydrant. Hydrophones should theoretically be capable of detecting lower levels of sound than aquaphones, but in British practice, the results have not been as satisfactory. This is probably due to two phenomena: there are many more fittings per kilometer of main to which an aquaphone probe can be attached than there are hydrants through which a hydrophone can be inserted; and secondly, hydrants were found to leak past the spindle when open, thus introducing an extra noise. (Grunwell and Ratcliffe, 1981, p. 25) These problems could be overcome by inserting the hydrophone directly through a tapping in the pipe wall.

Despite their infrequent use thus far, hydrophones may prove especially useful in developing countries, where the preponderance of non-metal pipe means that sound is not transmitted very well along the pipeline.

4.4 Factors affecting leak sound

There are many factors that affect the transmission and therefore the detection of a leak sound, most notably water pressure, leak size, pipe material and soil cover.

Pressure is important because it affects the amount of water flowing through a leak; some minimum pressure is required for the escaping water to make a detectable sound. Heim (1979, p. 67) states that it is usually necessary to have 15 psi (about 10 meters of head) or more for sonic leakage detection. Heath Consultants feel that a minimum of 20 psi, or 14 meters, is desirable and 10 psi (7 meters) essential (Heath, personal communication, April 1985). Bowen (1981, p. 65) claims that in systems running at pressures lower than about 50 psi, or 35 meters of head, leaks may be very hard to detect, even close to the source. This seems a little excessive; most other authors in the literature give the figure of either 10 or 14 meters.

Because so many systems in developing countries operate at low pressures, sounding may be difficult to carry out without temporarily increasing the pressure in the system, or at least in that portion to be investigated. In general, sounding is often done at night, when system pressures are expected to be higher and when there are fewer other noises. But in developing countries, the pressures may be no higher at night. In a large unaccounted-for-water study in Bangkok, the consulting engineers were not able to measure leakage directly, partly "because generally low system pressures reduce leak noise and cause a high proportion of customers to draw water at night. Thus night sounding and flow measurement are ineffective for leakage locating and quantification." (CDM-MEC, 1983, p. S/5)

The volume of water leaking, which is related to the size of the opening and to the pressure in the system, also has a bearing on the leak sound. Heath Consultants claim that 1/2 gal/min., or 2.4 m^3/day, is roughly the size of the smallest leak that is generally detected (Heath, personal communication, April, 1985).

Soil cover is a factor to be considered in indirect sounding. The depth of cover is obviously important -- the deeper a main is buried, the less the leak sound will be heard at the surface. The type of soil cover also comes into play; sandy soils are the best sound transmittors, and clay the worst (Bowen, 1981, p. 65, and Heim, 1979, p. 68). And finally, the ground surface upon which the geophone is placed affects the transmission of the sound to the instrument: sod tends to muffle any sound, whereas asphalt and concrete resonate well and also give a more uniform surface for the instrument (Heim, 1979, p. 68). Because of this, some leak detection crews carry a metal or wooden plate to place under the "foot" of their geophone in grassy areas; the plate resonates well and provides a uniform surface.

For direct sounding, the type of pipe material and the size of the main are of the utmost importance. Metallic pipes are by far the best conductors of sound. According to both Heim (1979, p. 68) and Bowen (1981, p. 65), sounding can be done on any type of pipe; the nonmetallic pipes just require a smaller distance between soundings. Bowen ranks pipe materials in order of decreasing sound transmittance: first copper, then steel, cast iron, ductile iron, plastic, asbestos-cement, and lastly concrete.

Smaller mains transmit sound better than large ones. The sound carried along the pipe is mostly that of the pipe vibration at the orifice, and mains with a larger mass will not vibrate as much (Heim, 1979, p. 68). As an illustration, a leak which could be heard with an aquaphone one block away on a 150 mm. line may be hard to hear 3 meters away on a 600 mm. line (Bowen, 1981, p. 65).

4.5 General procedure for sounding

Sounding is usually carried out in two stages: searching and pinpointing. In the first, direct sounding is performed on accessible points of the distribution system (hydrants, valve boxes, corporation stops), with notes made of all "noisy" points. Every corporation stop can be sounded, or only selected ones; the NWC has found that sounding every corporation stop is nearly always more cost-effective (NWC, 1980, p. 120). The East Bay Municipal District in California does not check all "services," but checks them at intervals of 150 feet (about 45 meters) or less (Rago & Crum, 1976, p. 2). Sounding of the corporation stops is sometimes combined with meter-reading.

In the second stage, pinpointing, the detection crew returns to investigate each case. If sounds were heard at two adjacent hydrants or valves, the surface is sounded between them to pinpoint the leak. If previous flow measurements indicated a leak in an area where nothing was heard by direct sounding, indirect sounding is undertaken to try to locate the leak. If a sound was heard at a corporation stop during the searching stage, it should be checked again later to ensure that it was not due to legitimate use within the house the first time. If the sound is heard again, the stop is closed and sounded again. If the noise is still heard, the leak is on the utility's property; if not, it is on the customer's side. (NWC, 1980, pp. 120-121)

In some cases, the search phase may include surface sounding at regular intervals as well as direct sounding at all contact points. Because sounds do not transmit well along large diameter pipes, Heim recommends that direct sounding always be supplemented with surface sounding for mains 12 inches (300 mm.) or more in diameter (Heim, 1979, p. 68). From the context, he seems to be speaking of metal pipes; for non-metallic pipe, the recommendation should probably be made for all sizes of pipe.

Heath Consultants feel that a comprehensive search on any system should include surface sounding at two-meter intervals in addition to direct sounding at all contact points for pipes that are less than four meters below the surface. (Heath, personal communication, April, 1985)

The amount of pipe that can be sounded in a day will depend on the characteristics of the system, and on the level of experience of the crew. The Office of Water Resources of the North Carolina Department of Natural Resources and Community Development finds that a three-person crew with a truck can cover about 10 miles a day on the search phase of a leak detection survey. One person drives a truck, the other two sit on the tailgate and get off at every hydrant and valve for direct sounding (Maynard, personal communication, 1985). Heath Consultants find they normally cover 3-6 miles a day in their search inspections. When doing a total search-and-pinpointing survey, they cover

2-4 miles a day, depending upon local conditions and the amount of leakage encountered. (Heath, 1985b, p. 1) The National Water Council finds that one person can effectively sound the access point corresponding to 20 properties (direct sounding) in one hour in urban areas (NWC, 1980, p. 121).

4.6 Problems with sounding

Sounding programs rely on the principle that the point of maximum sound intensity is the closest point to a leak, but there are a number of situations in which that does not hold true.

Figure 5 shows some cases in which direct sounding will not lead the investigator to the correct segment of main. Figure 5 shows a higher reading at hydrant B than at hydrant A, although hydrant A is closer to the leak. This is because of the tee in the pipe between the leak and hydrant B. Tees, elbows and other fittings consistently amplify sound and cause errors in judgement (Bowen, 1981, p. 65). This is one of many reasons why it is important to have a good map of the distribution system.

In Figure 5b, the farther hydrant, hydrant B, again shows a higher reading than the one close to the leak; in this case, the sound was deadened at a joint between hydrant A and the leak. Cast-iron mains with lead joints conduct sound very well; other types of joints may muffle the sound; and in mains where the sections are separated from each other by gasket joints, the sound will be confined to the leaking section (Bowen, 1981, p. 65).

Figure 6 gives some examples of problems encountered in indirect sounding. Because soil cover affects sound, any repair or other excavation that backfilled the hole with a material different from the original backfill will cause a distortion in the pattern of sounds heard on the surface. Hence in Figure 6a, a higher reading is obtained at point B because sound is transmitted better through the backfill there than at point A, directly over the leak. Records of previous repair work can not solve this problem, but can alert the investigator that it may be difficult to locate the leak.

Figure 6b shows a case where a varying depth of cover causes the leak sound to be most intense at point B, although B is not directly over the leak. The lower elevation at B means a shorter travel path for the sound wave than to point A. Investigators should therefore be conscious of elevation changes with respect to the pipe grade. Again, they will not be able to predict exactly where the leak is, but will understand why they might not find it on the first excavation if they rely only on sounding techniques.

In Figure 6c, a higher reading is obtained at point B, the farther point, because the asphalt surface carries the sound better than the grass at point A. As in the previous two cases, there is no exact way to compensate for this phenomenon, but investigators should be aware of the distortions caused by varying surfaces.

Another complication, shown in Figure 6d, is that of two leaks in close proximity. Point B, between the two leaks, has a higher reading than either of the meters directly over the two leaks, because the combined sounds are being registered. There is no way to predict this occurrence, but because of the possibility of multiple leaks, some crews make it a point after every repair to recheck the previously noisy hydrants in the area.

A final limitation of sounding, related to those mentioned above, is that some leaks have no clear maximum sound associated with them. In addition, some leaks produce so little sound that background noise (such as traffic) may hide the noise completely,

4.7 Other detection methods

There are several methods of leak detection, distinct from the sounding techniques, that can overcome the problems shown in Figures 5 and 6.

4.7.1 Leak Noise Correlator: The correlator is a more sophisticated instrument than the aquaphone or geophone; it analyzes the sound waves received simultaneously at two different points on the distribution system (for instance, hydrants A and B in Figure 3) to calculate the exact distance to the leak. Whereas a person using an aquaphone would compare the relative intensities at the two hydrants to estimate where the leak must be in relation to the two hydrants, the correlator compares the wave forms and progressively delays one with respect to the other till the forms are identical, thus calculating the time of travel from the leak to each listening point.

Because a correlator does not depend on detecting the point of maximum intensity, as do the other locators, it can be used in those situations where there is no clear maximum, where the maximum does not coincide with the leak, where the leak noise level is so low as to preclude surface (indirect) sounding, where several leaks exist in proximity, or where background noise masks the leak noise (Grunwell & Ratcliffe, 1981, p. 7).

Although leak noise correlators have performed well in trials (e.g. Grunwell & Ratcliffe, 1981, p. 33), Moyer et al., found that surveying by sonic detection was highly accurate and stated that "although there are other leak detection methods in use which are more accurate, they may often be prohibitively expensive." (1982, p. 358) Most of the American literature, in fact, reflects the idea that correlators are too expensive for individual utilities to own, and should be used only as a contract service (e.g., Heim, 1979, p. 69). A noise correlator typically costs around $50,000 (Heath, personal communication, April, 1985), whereas a kit containing an electronic aquaphone, electronic geophone, pipe locator and valve locator can be bought for about $1200 to $2500 (Maynard, personal communication, 1985).

4.7.2 Gas tracers: Another method of leakage detection, even less common than the correlator, is that of gas tracers. A gas is inserted into the pipe, either dissolved in the water or put into a dewatered pipe, and detected when it escapes through the leak, thus pinpointing the leak (see Figure 7). Holes are sunk along the pipe at intervals, usually referred to as bar holes because they are sunk with a bar of some type. For heavier-than-air gases, the holes must extend down to the main; for lighter-than-air gases only shallow holes are required, if any.

Heim (1979, p. 69) lists four different tracer gases used for leak detection. His conclusion on tracer gas surveys is that they are "extremely expensive" and "should only be considered when sonics are completely impractical."

In the United Kingdom, various tracers have been tried, with nitrous oxide being the most common method used until recently. A new tracer method has been developed, however, which has produced good results and is now recommended by the NWC. The gas is sulphur hexafluoride (SF_6), and it offers a number of advantages (See NWC, 1980, p. 125). The NWC recommends the tracer technique when no leak noise can be detected in a segment of main where a leak is known to exist, and suggests that it is particularly suitable for rural mains and trunk mains where there are few fittings for direct sounding. One of its drawbacks in urban areas is the problem and cost of digging and repairing bar holes in roadways.

This method should be kept in mind for problem leaks, but probably does not have much immediate application in the small systems we're considering here. If anything, it should be considered as a possible leak detection method to be performed by contractors who are experienced in the technique.

5. LEAKAGE CONTROL POLICIES

As stated in Chapter 4, a leakage control program is designed to reduce the leakage, or to maintain it at a lower level than would be the case without such a program.

The amount of leakage that remains undetected and unrepaired in a water system depends on the level of resources devoted to leakage control. Theoretically there is some level of leakage beyond which any further efforts at leakage reduction would cost more than the benefits of the additional water saved. It can never be economically feasible to eliminate leakage completely.

An ideal leakage control policy, then, would be to reduce leakage in a system to the optimum level and keep it there. That optimum may change over time, as the cost of water or the costs of the leak detection methods and equipment change, and the control program would be adjusted accordingly.

In practice, however, this approach is rarely taken. Determining the optimum level of leakage for a given system requires in-depth information on the costs of leakage control programs (which depend in part on the characteristics of the distribution system), the total amount of leakage in the system, the effectiveness of each type of leakage control, and the value of the water (which depends in part on future demands on the system). This is information which is not often readily available, and which, as some authors point out, requires a substantial investment to gather. For instance, when discussing measurement of leakage in a water system, Ridley (1983, p. SS16-2) states that "the biggest cost is often found to be the updating of system records which is an obvious precursor to any rational analysis." Calculation of the value of water is an extremely important issue, and will be discussed separately in Section 5.5.

This "optimum" level of leakage is usually described in terms of the economic value of the water saved; but there are a number of other benefits that accrue from a reduction in leakage, benefits both to the utility itself and to society at large. After preparing for and implementing a leakage control program, the utility will have more thorough records on the water system, information which will be valuable in other aspects of system management as well. This type of benefit is difficult to measure. The spin-offs from leakage reduction that affect the general public are generally not quantifiable either. A reduced chance of leaks surfacing, freezing and causing fatal accidents; a reduced chance of property damage; improved relations between the customers and the utility; reduced potential for outbreaks of waterborne disease; an increased number of people served -- all these are social benefits of leakage reduction that make leakage reduction more attractive than the dollar value of water saved would indicate.

Given the difficulty of determining the optimum level of leakage, policies are often defined instead with arbitrary goals: reducing the amount of lost water to some predetermined level, for instance. In many cases, no policy is made explicit; leakage detection is carried out with the techniques, equipment and expertise which are available -- which may mean hiring a consulting firm. And in the vast majority of systems worldwide, nothing is done at all. The reasons cited in the Introduction for this apparent lack of concern (shortage of resources, lack of awareness of the problem, lack of records on the system) apply to most small systems in industrialized countries as well as to systems throughout the developing world.

In the remainder of this chapter, explicit and implicit leakage control policies from around the world are presented. The British position is described in detail, as an example of a well-developed national policy, and then approaches taken by utilities or water agencies in the U.S. and in other industrialized countries are presented. In all cases, the policies are examined with regard to their applicability to developing countries, as well as on their own merits. A few case studies from developing countries are presented. The importance of establishing priorities for leakage control is stressed. Finally, the value of water is discussed.

5.1 The British (National Water Council) approach to leakage control

5.1.1 Background

The British have been able to develop national guidelines for leakage control because of the centralized organization of their water supply sector. When most of the water sector in England and Wales was amalgamated into ten Regional Water Authorities in 1974, the wide variation in treatment of losses among the individual water systems became unacceptable, and it was felt that a logical, unified, approach to leakage control was needed. A Technical Working Group on Waste of Water was set up by the Department of the Environment and the National Water Council (NWC); this Group produced a final report in 1980, based on extensive research and on field work carried out under the guidance of the Water Research Centre. The 1980 report, published by the NWC and entitled Leakage Control Policy and Practice, presents a methodology for determining an optimum leakage control policy, as well as describing the state-of-the-art in control techniques.

The methodology presented in the NWC report has been approved by the water industry throughout the the United Kingdom, and the Water Authorities have agreed both to apply the method to determine the level of leakage control appropriate to different parts of their systems, and to carry out the control as soon as practicable. (Ridley, 1983, p. SS16-1) In fact, the procedure developed in the NWC manual has become the only method for determination of a leakage control policy that is acceptable to the British government. Before securing funds for major new capital schemes, a Water Authority must demonstrate that leakage in the designated area has been reduced to economically acceptable levels. (Goodwin & McElroy, 1983, p. 32)

5.1.2 The procedure

The procedure described in the NWC report consists of the following steps:

(a) initial measurement of the magnitude of leakage within the system;

(b) determination of the benefits of reducing leakage (by calculation of the unit cost of leakage);

(c) estimation of the costs and potential savings of pressure control;

(d) calculation of:

 (i) the cost of operating each of the methods of leakage control;

 (ii) the cost of leakage appropriate to each method of leakage control;

(e) comparison of the sum of the costs in (d) (i) and (ii) for each leakage control method to determine which methods are economically acceptable;

(f) consideration of local factors;

(g) decision on the leakage control method to be adopted;

(h) determination of the operational resources required;

(i) implementation of appropriate action;

(j) monitoring of performance at regular intervals.

(NWC, 1980, p. 13; and Ridley, 1983, pp. SS16-1,2)

One of the main features of the NWC manual is its emphasis on a rational economic approach to leakage control. Whereas there is little agreement internationally on how to calculate the benefits of water saved by leakage detection, the Working Group was able to develop a method of calculating the cost of leakage "which found acceptance by engineers, economist and accountants in the UK" (Ridley, 1983, p. SS16-2).

The basis of the British approach is to calculate the total cost of each method of leakage control, and to choose the method with the lowest total cost. The "total cost" includes both the cost of carrying out that leakage control method and the cost of the leakage level appropriate to that control method (i.e. the cost of the water lost under that method). If there are several methods within the same cost range as the least costly method (i.e. within 20% of the lowest cost), local non-quantifiable factors are taken into consideration for the final decision.

Before describing the procedure in greater detail, the different methods of leakage control proposed by the NWC are summarized.

5.1.3 Methods of leakage control

Six methods of leakage control are described, all of which are currently practiced by different water systems in the U.K. The six methods are passive control, regular sounding, district metering, waste metering, a combination of waste and district metering and, finally, pressure control, which differs from the other methods in that it is not a method of locating leaks for repair, but rather of lowering the overall leakage rate. These methods are described in turn.

(a) Passive control consists of repairing only those leaks that are brought to the attention of the utility by customers or discovered during normal operations. It is the most basic form of leakage control, in practice almost everywhere, and allows the highest level of leakage to pass undetected.

(b) Regular sounding is the simplest method of active leakage control, and consists of systematically sounding all hydrants, corporation stops, valves and other convenient fittings on the distribution system at regular intervals, as described in Chapter 4. The frequency of inspection varies from one system to the next; the NWC manual recommends yearly inspections, with an acceptable range of six months to two years between inspections. (NWC, 1980, p. 49)

The manual also mentions briefly the possibility of "differential sounding," which consists of dividing a system into a number of sections, with records kept on the number of "faults" found in each section. These records are then used to determine the future frequency of inspection for each part of the system; areas with more faults are then sounded more frequently. (NWC, 1980, p. 95)

(c) District metering involves the installation of flow meters throughout the system in such a way as to measure flow into the different sections, or "districts." The NWC defines these districts to include about 2,000 to 5,000 properties each. The total flow into each district is read from the meters at regular intervals, and the results analyzed over time. If an unexplainable rise in the total flow is noted for a particular district, a sounding team is sent in to search for leaks.

A problem with this method is that if considerable leakage exists when district metering is begun, that level of consumption is taken as the norm. Consequently, it is recommended that all measurements be converted into units of liters/property/hour (l/prop/hr) so that districts can be compared against each other and any high levels immediately investigated. (Bays, 1984, p. 54)

This method of leakage control offers the advantage (over regular sounding) of identifying those areas where leakage is expected to be highest, so that sounding crews will be obtaining the highest returns from their efforts.

The NWC manual recommends that the district meters be read once a week, with a range of 1 to 30 days acceptable; and that regular sounding be carried out on the whole system at the frequencies given above. (NWC, 1980, p. 49)

(d) Waste metering is a more refined method of leakage control; more costly and more effective in reducing leakage than district metering. In waste metering, areas are identified that can be isolated by valves in such a way that they are supplied by a single pipe, in which a flowmeter can be installed. The flowmeter must be capable of measuring low rates of flow, and is referred to by the British as a "waste meter."

Waste meters, which can be installed permanently or temporarily, are normally used only to measure night flow rates. The minimum night flow is compared to previous values or to some predetermined level, and any waste area with high values is then investigated. This is often done by a "step test": closing off successive portions of the waste district by closing valves and noting the accompanying drop in flow to the area. In this way, the leaking segment of main can be located, and a sounding crew sent in to pinpoint the leak in a relatively small area.

The NWC suggests that waste districts comprise about 1000 to 3000 properties, and notes that night flow measurements are made anywhere from 1 to 11 times a year, with four times a year being most common (NWC, 1980, p. 96).

(e) Waste/district metering is a combination of the two methods in which districts with abnormally high flows are then investigated further by waste metering.

(f) Pressure control, as mentioned earlier, is not a method of locating leaks but rather of reducing the overall rate of leakage by lowering both the rate of development of new leaks and the volume lost through each leak. The NWC feels that pressure control should be investigated in every case, in addition to the other methods of leakage control.

5.1.4 Measurement of leakage

The NWC manual (Leakage Control Policy and Practice) stresses the importance of obtaining as accurate a measure of leakage as possible, given that the figure for the leakage level will be used in economic calculations involving large sums of money and affecting operations for many years into the future (NWC, 1980, p. 41).

The manual describes two methods of estimating the total amount of leakage in a system: a) total integrated flow, and b) total night flow rate; and strongly recommends the use of the latter. In both cases, leakage is approximated by unaccounted-for water measurements.

The measurement of leakage by the total integrated flow uses the formula given in section 2.2, that is:

$$U = S - (M + aP)$$

where U = unknown or unaccounted-for quantities of water

S = sum of all inputs into the system

M = sum of all water accounted for by measure

a = average domestic consumption per capita of population plus an allowance for unmetered commercial consumption

P = [unmetered] population supplied

Because all the terms in this formula are subject to seasonal variation, it is essential that each quantity be measured over the same time period.

The NWC does not recommend the use of this method, because although it is relatively simple, total integrated flow is the less accurate method. This is because of the errors inherent in subtracting two large numbers (S and (M + aP)), each subject to certain errors, to obtain a relatively small number (U). (NWC, p. 1980, pp. 92-93)

The method recommended by the NWC makes use of flow rates rather than total quantities of water, and relies on the principle of measuring flows during the night, about 3 a.m., when flow is at a minimum. After eliminating the small amount of known consumption, the remainder is ascribed to leakage. This method uses the modified formula

$$U' = S' - (M' + a'N')$$

where U' = unknown or unaccounted-for night flow rate

S' = sum of all input flow rates into the system (minimum night flow)

M' = total night flow rate of all trade and commercial users

a' = average domestic night flow rate per property

N' = number of properties supplied

Mathematically, this method is more accurate than the first formula (for total integrated flow) because at night, both the commercial use (M') and the domestic use ($a'N'$) are low, so that small quantities subject to certain errors are being subtracted from a relatively large quantity (S') to obtain another relatively large flow. (NWC, 1980, p. 93) This flow is expressed in liters per property per hour (l/prop/hr) for leakage from urban distribution systems, or as liters per hour per kilometer of main (l/hr/km) in rural systems.

In many systems, S' (the night flow) can be measured by cutting off supply to the controlling service reservoir and measuring the amount by which the level of the reservoir drops. M' (trade and commercial use) is obtained by a direct reading of the meters for large consumers, combined with estimates of night flow for smaller metered users.

From their field experiments, the NWC has found that average domestic night flow (a') is on the order of 2 l/prop/hr. (NWC, 1980, p. 94) What remains, then, is U', the net night flow rate in l/prop/hr., which is actually unaccounted-for water, but which is mostly comprised of leakage; the net night flow is commonly referred to as the leakage level throughout the NWC manual.

5.1.5 Calculation of unit cost of leakage (step (b) of the procedure)

The unit cost of leakage is needed to calculate the economic benefit that would be obtained by changing leakage levels. Rather than considering it as the "value" of the water lost, the NWC defines this benefit as the effect, upon the expected costs of supplying water, of the change in demand brought about by a change in leakage. They point out that past expenditure can in no way be affected by a future change in demand and is therefore irrevelant. The change in future costs, which is the relevant figure, is the saving effected by a reduction in leakage, and consists of two distinct elements: (a) a reduction in annual operating costs, and (b) a deferment of demand-related schemes effecting a reduction in the programmed capital investment. (NWC, 1980, p. 37)

The NWC report goes into great detail in describing how to calculate each component of the operating costs and capital costs. The procedure takes into account not only how a reduction in demand would affect each supply source and pumping station individually, it also presumes knowledge of capacity expansions over the long term. The procedure is (necessarily) complex and can only be recommended for all water systems because of the regionalized structure of the water sector in the United Kingdom, which provides technical resources and planning for water systems of all sizes.

5.1.5.1. <u>Annual operating costs</u>

These costs consist of pumping costs, water treatment costs, and bulk purchase costs (if water is purchased). As mentioned before, only those sources or pumping stations that will be affected by a reduction in demand are considered. After calculating a unit operating cost for each source, the unit operating cost for the entire system is calculated as the average of these individual unit operating costs, weighted according to the likely magnitudes of the reductions in supply at each source. (NWC, 1980, p. 58)

5.1.5.2 <u>Annual capital cost</u>

The calculation of the annual capital cost is more complicated. The method proposed by the NWC is actually a type of marginal cost calculation, although they do not refer to it that way. Their "discounted unit capital cost" corresponds to the "average incremental cost" widely used by the World Bank in dealing with water supply systems, and described in the World Bank paper on alternative concepts of marginal cost and the water supply sector (Saunders et al., 1977).

The NWC manual presents several charts for use in setting out the costs of those capital schemes required to satisfy future demands, incorporating corrections to allow for future schemes beyond the current planning horizon, and "demand multipliers" (0-1) to indicate the portion of the scheme that is capable of being deferred. The NWC manual describes the procedures in detail and gives several examples (pp. 37-40, pp. 55-74).

5.1.6 Consideration of pressure control (step (c) of the procedure)

Because pressure reduction can be implemented fairly quickly and savings realized immediately thereafter, the British recommend that pressure reduction be considered for any system.

The NWC attaches so much importance to pressure control partly because of results of its field experiments. It was discovered that when measuring overall leakage in a system, the leakage reduction caused by a given pressure reduction is greater than that predicted by hydraulic theory. (This is believed to be due in part to the changing size of the orifice at different pressures.)

Figure 8 shows the pressure-leakage relationship expected from the theoretical square-root law (the dashed line), and the actual relation observed through experimentation (the solid line). "Thus," concludes the NWC, "quite small reductions in high pressure will cause a correspondingly greater reduction in leakage." (NWC, 1980, p. 36)

Several observations are in order here. First, this dramatic effect of pressure reduction occurs only at "high pressures," as stated in the NWC manual. At lower pressures, then, pressure reduction is not as effective. Several authors have overlooked this point, however, and misquoted the NWC results. Goodwin & McElroy (1983, p. 32) state that "Experiments have shown that a given reduction in pressure causes a proportionately greater reduction in leakage," and Ridley (1983, pp. SS16-2,3) tells us that "It was found that leakage within a distribution system does not vary with the square root of the pressure as understood from basic fluid mechanics but that the relationship is such that a reduction in pressure causes a proportionately larger reduction in leakage." Neither article adds the important qualification that this is true only for "high" pressures.

It is interesting to examine the data from which the solid curve in Figure 8 was derived. Figure 9, from the detailed report The Results of the Experimental Programme on Leakage and Leakage Control (Goodwin, 1980) shows the original data. Figure 9a shows the data collected; there is not a unique relation between pressure and leakage, because leakage depends on so many other factors as well. Figure 9b shows the same data "scaled to take out the unwanted variation" (Goodwin, 1980, p. 27). The solid line in Figure 8 was taken directly from Figure 9b, at an arbitrary scale that does not necessarily correspond to that of the theoretical (dashed) curve shown in Figure 8. Because the scale in Figure 8 is arbitrary, it is incorrect to have the horizontal axis (pressure) labelled. The graph gives the impression that at pressures of less than about 20 m, the slope of the solid (actual) line is less than that of the dashed (theoretical) line, which would mean that in that pressure range, the actual reduction in leakage corresponding to a given pressure reduction is less than that predicted by theory. But the slope depends on the scale, which may be different for the two lines. The "high" pressure above which this observed relationship holds true will vary from system to system.

It is also important to note that the raw data (Fig. 9) were only collected at pressures greater than about 10 m, so there is no empirical evidence at the lower pressures commonly encountered in developing country water systems.

A figure is presented in the NWC manual for use in calculating the change in net night flow that can be expected for a given pressure reduction, derived from the relationships shown in Figures 8 and 9. A method is also presented for converting this reduction in net night flow into an equivalent reduction in overall daily leakage, given that pressures are generally lower in the day than at night. From their experience, the British have found that multiplying the night flow ratio by 20 hours generally gives a satisfactory estimate of the daily leakage.

The interested reader is referred to the NWC manual (pp. 42-43, 98-100); the figures are not reproduced here because they are specific to the United Kingdom.

5.1.7 Calculation of total cost of each control method (step (d) of the procedure)

The basic NWC approach, as explained above, is to calculate and compare the total costs of each method of leakage control, where the total cost is the sum of 1) the cost of implementing the control method, and 2) the cost of the amount of water lost under that particular control method. Being able to calculate the cost of the water lost for a particular control method before implementing that control method is dependent on being able to predict the level of leakage that will occur under that method of control. The British are able to do this only because of data they collected during years of field research on the levels of leakage in systems already practicing the various control methods.

5.1.7.1 Prediction of leakage levels (step (d)(i))

The total cost of leakage for a given control method will be equal to the unit of cost of leakage multiplied by the amount of leakage expected for that control method.

Table 3 shows levels of net night flows in large urban areas, a table presented in the NWC manual (NWC, 1980, p. 36) for use in predicting the level of leakage to be expected for any of the five control methods (excluding pressure control). A method is presented in the manual for converting net night flows into equivalent daily values, taking into account that pressure is generally lower during the day than at night. (see NWC, 1980, pp. 42-43, 98-100)

The distinction between low, medium and high levels of leakage made in this table is a way of taking into account the factors other than control method which affect leakage (such as age of system, soil conditions, etc. -- see Figure 2), without making these factors explicit. The assumption is presumably that these factors will remain the same when the leakage control method is changed. It is interesting to note that in their overall recommendations, the NWC states that "Investigations did not reveal a correlation between magnitudes, probability of occurrence of frequency of leakage and any feature of design, construction or arrangement of a distribution system or its constituents. Any further investigations will necessitate the expenditure of large sums with little hope of definite conclusions," and therefore recommends formally that "No further work should be carried out at the present time in investigating the mechanisms of leakage and its points of occurrence." (NWC, 1980, p. 18)

To determine whether a utility has intrinsically "low," "medium," or "high" leakage levels, the value for existing leakage in the system is compared to the figures on the chart for the method of leakage control currently in practice. For those cases where the existing value lies between those given in Table 3, Figure 10 can be used instead. (NWC, 1980, p. 45) For instance, a utility with 20 l/prop/hr net night flow under passive control can expect a net night flow of 11 l/prop/hr with regular sounding.

Both Table 3 and Figure 10 were prepared for urban areas. For rural areas, higher levels of leakage per property are expected because of the longer lengths of main. However, approximations can be made by artificially increasing the number of properties to a figure typical of a urban area with the same length of mains, and using that artificial figure for leakage per property in Figure 10. (NWC, 1980, p. 44)

Of course, the figures in Table 3 are only average values, and a wide range can be expected in practice. It is interesting to note that when summarizing the NWC manual, Bays (1980, p. 54) presents a table of typical net night flows that does not correspond exactly with the NWC table reproduced in Table 3. For instance, for passive leakage control he gives a figure of 20-25 l/prop/hr (on the high end of the figures in Table 3), and for waste metering and combined district/waste metering he gives a figure of 5-6 l/prop/hr (the values for low to medium leakage in Table 3). No explanation is given for the difference.

As in the case of the leakage-pressure relationship, it is informative to examine how the figures in Table 3 and Figure 10 were derived. The data collected were actually mostly for areas with waste metering (net night flows of 2-12 l/prop/hr., with a mean of 6.1), and passive control (net night flows up to 50 l/prop/hr., with a mean of 18.6). (NWC, 1980, p. 34) The raw data are shown in Figure 11. To obtain Table 3, then, the data were "extended to include likely night flows in areas subject to other methods of control; it is important to note that these additional figures are based on the limited amount of data available and also on interpolation. The effectiveness of combined district and waste metering has proved difficult to estimate; however, net night flows are likely to be similar to those in areas with waste metering." (NWC, 1980, p. 36)

The figures in Table 3 and Figure 10, then, which are to be used in the decisions involving "large sums of money and affecting operations for many years into the future" that were mentioned earlier, are somewhat tenuous. But based on the available data, this is the best that could be done in developing a rational policy; data will continue to be collected as more utilities choose to use active leakage control, and the information can be updated.

5.1.7.2 Calculation of costs of leakage control methods (step (d)(i))

Table 4 gives the costs of components of leakage control methods in the United Kingdom. The range of costs is interesting; the actual figures themselves (as is true for any other actual figures presented in this section) depend on conditions in the U.K. and would not be applicable elsewhere.

5.1.8 Final choice of method

After calculating the total cost of each method of leakage control, the uneconomic options (those with a total annual cost greater than 20% above the minimum total cost) are identified and discarded. The final choice is determined by local factors such as the unquantifiable benefits of more intensive leakage control, or constraints on the different methods (financial or political constraints, human resources, existing equipment, etc.).

5.1.9 Status of leakage control efforts in the U.K.

Since the publication of the NWC manual Leakage Control Policy and Practice, in 1980, considerable effort has been expended in the UK on implementing the recommended procedure. As of 1983, efforts had been mostly directed at determining the appropriate leakage control policy. Measurement of net night flows had been performed for about 50% of the country. (As an example of what that represents, one of the ten Regional Authorities had measured net night flows for 290 different zones, covering 85% of the 2 million properties in its region.) The unit cost of leakage had been calculated for about 70% of England and Wales, and several Authorities were at the stage of determining which control policies would be appropriate for their regions. It was only over the next few years that they planned to undertake the "much more difficult, expensive and labour intensive task of implementing those policies in the expectation of significant financial benefits." (Ridley, 1983, pp. SS16-3,4)

It is impressive to see how much has been accomplished in the United Kingdom along the lines of leakage control, but at the same time sobering to realize how long it takes to fully implement the procedure recommended by the NWC. Three years after the NWC manual had been published, data collection was still underway in most systems, and the actual implementation of the leakage control policies that were to be chosen was not to take place for another several years. The benefits of the leakage control programs are expected to be significant and to justify the considerable expenditures necessary to reach the actual stage of implementation of the control programs; but those benefits will only be realized five or more years after beginning to focus attention (and resources) on the problem of leakage.

5.1.10 Problems of applying NWC approach to developing countries

As mentioned several times above, the data and figures presented by the NWC are taken from water supply systems in the United Kingdom. Therefore, their recommendations cannot be applied to other countries - especially not to developing countries, where conditions are very different. Pressures are lower, pipe materials different, costs of water production different, costs of labor lower - all the variables underlying the NWC analyses are different. This applies not only to recommendations on the final choice of control method (for instance, the finding that waste metering is almost always justified in areas where the unit cost of leakage is 3 p/m^3 or greater - NWC, 1980, p. 48), but also to recommendations on the methods, such as size of districts or frequency of sounding - all these figures will almost certainly be different in a developing country.

Although the quantitative results cannot be adopted by developing countries, the overall approach would appear to be applicable. The steps outlined in section 5.1.2 could be followed by any water system or regional authority in developing a leakage control policy. There are problems here, too, however.

The main obstacle to using the NWC procedure for determining appropriate leakage control methods in developing countries is that it requires such an investment in time and money before any savings are effected. The NWC procedure requires extensive information on each water system, and assumes that skilled personnel are available to calculate the unit cost of water, to operate equipment, and so on. For the small systems discussed here, those resources are not available, and the prospect of such extensive data requirements would discourage the managers of these systems from taking any action whatsoever on leakage control. As is discussed in Chapter 6, rather than assume complete information must be available on the distribution system and the cost of leakage, it may be better to accept a less-than-optimum solution and begin some leak detection efforts while gathering the information necessary for long-term management.

In addition to the difficulty of carrying out the full NWC procedure for determining the appropriate policy, there are technical obstacles to practicing the individual methods of leakage control. To practice waste metering, it must be possible to isolate small portions of the distribution system, which requires full knowledge of the underground network and of the location and condition of valves. Even if this information were available, it may not be physically possible to isolate portions of the network. Waste metering also relies on the assumption that consumption is lower at night, which is often not the case in developing countries where there is often insufficient supply during the day to meet all demands. District metering does not require subdivisions as small as those for waste metering, but it still requires the capability of isolating portions of the network. The only method of leakage control immediately available to an existing water system with few records on the distribution network is that of sounding - and even sounding requires some knowledge of the distribution system to be effective. Sounding also requires a certain minimum pressure in the pipes, which may not be possible in many systems.

In summary, then, although the National Water Council has developed a thorough approach to leakage control, there are several reasons why their methods cannot be of immediate use for small water systems in developing countries: 1) the specific recommendations are based on field data from the United Kingdom and will not apply to other countries; 2) the overall management procedure requires more resources than are currently available in most of these systems; and 3) there are technical limitations and budget constraints which mean that the full range of control methods described in the manual are not available for the systems under consideration.

5.2 Approaches to leakage control in the United States

Because of the decentralized nature of the water supply sector in the United States, there is no national policy such as that set forth by the National Water Council in the

United Kingdom. Nevertheless, there is a growing awareness of the general problem of unaccounted-for water, and a number of utilities (especially large ones) have developed their own approaches to the problem.

In 1984, the Research Foundation of the American Waterworks Association sent a survey to more than 1200 utilities of all sizes, "in an effort to collect information on one of the most common problems facing water utilities today - unaccounted-for water or water loss" (Water Research Quarterly, 1984, p. 12). The informal questionnaire asked the different utilities whether they had a water loss problem or had studied it, what the major causes of their water loss were, and what techniques had been used to deal with the problem.

Among the 376 respondents, "approaches to the leakage problem varied widely, from a passive program of waiting until a leak surfaced before repairing it to the more aggressive stance of hiring a firm with state-of-the-art equipment and technical expertise to search out leaks." In fact, the Water Research Quarterly (1984, p. 12) reported that one-third of those utilities reporting problems with leakage have used outside leak-detection services - either on a one-time basis, an annual contract (for the whole system or for a certain percentage each year), or even on a trial basis (to be continued if a significant amount of leakage was found in a pilot zone).

(There are a number of United States firms offering their services in leak detection, but there are two that are especially well-known and contribute most to the literature. These are Heath Consultants and Pitometer Associates. Heath focuses mostly on actual leak detection, whereas Pitometer often does complete water audits. Both sell leak-detection equipment, and provide training, and both have worked overseas as well as in the U.S.)

Among the utilities responding to the AWWA questionnaire, those wnich actually practice some form of leakage control themselves usually include it as part of their regular maintenance procedures (sounding meters as they are being read, testing hydrants for leaks during flushing, etc.). Some practice regular sounding, others keep track of management records over time (as in the British district metering approach).

It is significant that neither the report in the Water Research Quarterly nor, apparently, the survey itself, contained any mention of economic or financial considerations. There was no analysis of either the costs or benefits of the varied leakage control programs, nor any mention of how the utilities decided upon leakage control programs - other than that "money and lack of personnel were the reasons most often cited for not having such a program." (Water Research Quarterly, 1984, p. 13) Most of the literature on leakage problems, in fact, other than the

British, neglects any economic analysis.

The general assumption in the literature is that leakage or unaccounted-for water should represent no more than 10-20% of total production. This generalized rule appears not only in the U.S. literature (cf. Cole & Cole [1980], Maynard [1985]), but is also reflected in literature on developing countries (cf. Estrada [1983] for Latin America, Nihon Suido [1973] for Indonesia, Mulekar [1983] for India). It is felt, therefore, that leakage at a level higher than 10-20% of total production automatically justifies leakage detection efforts, with no further analysis.

5.2.1 Sounding vs. flow measurement for leakage detection

"Listening" and "water audits" are described by G. Brewster Cole of Pitometer Associates and the AWWA Leak Detection Committee as the two basic methods of leak detection. Cole categorizes the various approaches to leakage into two basic methods: (1) listening and (2) a combination of flow measurements and listening that he refers to as a water audit (Cole, 1980a, p. 3). "Listening" is another term for sounding, and the water audit he describes is similar to the British "waste metering."

The principal advantage of the water audit over sounding, according to Cole, is that it produces an accounting of all water flowing through the distribution system. Also, only those districts with high "minimum night ratios" (defined below) or high night flows are investigated, thus saving time and money by comparison with a sounding program that covers the whole system. (Cole, 1980b, p. 3)

5.2.2 Minimum night ratio

Whereas the British report leakage as absolute night flow rates in l/prop/hr, Cole (1980b, p. 3) defines the "minimum night ratio" as the key index. This is the ratio of the minimum night flow to the daily average, and Cole states that if it is less than 35 or 40%, little leakage can be expected. If the minimum night ratio in any district is greater than 40%, there is probably excessive leakage in that district, and step tests should be carried out to identify the areas with high flows, which will then be investigated by sounding.

The "minimum night ratio" measure is cited by other authors as well. For instance, Curtiss (1983, p. 2) states that the ratio should be about 30 to 35% in a predominantly residential district, and that a higher ratio warrants further investigation. Siedler (of Pitometer Associates) states, like Cole, that any district with a minimum night ratio of greater than 40% should be subdivided and investigated further for leakage.

This ratio of minimum night flow to average daily flow depends entirely on the water use pattern. In systems with low pressures and intermittent supply, where consumers routinely collect water at night (as is the case in many developing countries), the ratio will be higher, even with no leakage. For this reason, any country or region using this method of district metering would have to find through experience the appropriate range of night ratios to expect. And since any leakage existing when measurements begin will be included as part of the norm, the night flow should actually be converted to standardized values (leakage per property, per person, or per kilometer) as recommended by NWC, rather than expressed as a ratio.

It should be noted in passing that Cole makes the implicit assumption that all "avoidable" leakage in the distribution system will be detected during the sounding phase, when he states that after tabulating leakage (found) and unauthorized use, and estimating unmetered public use and unavoidable leakage, the remainder that is unaccounted for (literally) must be ascribed to domestic use and waste or to meter under-registration. (Cole, 1980b, p. 3) That is not correct, however. The amount of leakage discovered depends on the procedure used for leakage detection (see Chapter 4). This is a point that is overlooked in all the literature; the quantity of leakage discovered during a sounding survey is usually presented as if that were the total amount of avoidable leakage in the system.

5.2.3 Economic analysis

5.2.3.1 Howe's "economic repair point"

One of the few articles in the American literature that discusses the economic aspects of leakage control is that of Howe (1971), an economist who based his analysis on data from Pitometer Associates.

Howe makes a distinction between the extent of *technically* avoidable losses and the portion that is *economically* salvageable (1971, p. 284). He uses the figure of 3,000 gpd/mile of main as "an engineering estimate of the physically irreducible minimum loss rate" (1971, p. 285). This is the figure for "unavoidable leakage" mentioned in section 3.6.3.1, developed by Kuichling in 1897 and quoted widely.

Howe's basic point is that there is some level of loss at which it "just becomes economically worthwhile to undertake the detection and repair of leaks." This "economic repair point" occurs for a leakage level "where the present value of the water currently being lost, but which might be saved, equals the cost of carrying out the detection and repair program." He develops an equation, using an interest rate of 6%, and a life of 20 years for the anticipated repairs; he then plugs in the "best estimate" for the average cost of the survey-and-repair operation ($200/mile of main) and is left with an equation relating the leakage rate to the "cost of water" at the critical point.

For every value of cost-of-water, a value for the critical level of leakage is calculated (in gpd/mile). Any leakage above that critical amount represents leakage that should be recovered. From data on the distribution of water leakage rates, Howe then develops a graph of "economic savings" (percent of total production) as a function of water cost, or in other words how much leakage reduction should be effected at each cost of water. He repeats this for a survey-and-repair cost of $400/mile of main.

Howe's final conclusions are that "at very modest costs of water, it pays to repair most leaks above 3,000 gpd/main mi.," and also that "the limit to economic savings as a percentage of total production is 9 percent," at least for the sample data used in his paper. (Howe, 1971, pp. 284-286)

The notion of a breakpoint at which the costs of survey-and-repair equal the costs of the leakage detected is intuitively appealing, and the analysis provides some useful insights into the problem of defining an optimal leakage control policy. However, there are a number of limitations to Howe's procedure and assumptions. (1) Howe makes the assumption mentioned earlier that all leakage above the magic figure of 3,000 gpd/mi. of main is technologically detectable; he also implicitly assumes that leakage can be reduced to some arbitrary level calculated as the critical level. Neither of these assumptions seems justified.

(2) Assuming one constant value of survey-and-repair cost is equivalent to assuming only one method of leakage control - he is apparently using the costs of a sounding survey. Other methods are available in the U.S., however. (3) No explanation is given as to how the "cost of water" was calculated. (4) No justification is given for assuming a 20-year lifetime for the anticipated repairs - it appears completely arbitrary. Other authors, in fact, discuss how difficult it is to choose a time period over which to integrate leak flows when calculating the total benefit of leak reduction. The assumption is sometimes made that underground leaks would only continue a few years before surfacing and being repaired under passive control. This problem of the time period over which leak reduction benefits are realized is an important one, and we return to it in Chapter 6.

5.2.3.2 Marginal costs and benefits

Hanke (1981) presents a marginal-cost analysis to evaluate the desirability of a leakage detection and control policy. The decision rule is that the program should be carried out if the change in benefits exceeds or equals the change in costs of detecting and repairing leaks. The change in benefits is the product of the quantity of water saved by repairing system leaks and the marginal cost of water. (Hanke, 1981, p. R107)

Theoretically, this is correct. If there is no limit on the money available for leakage control efforts, the optimum solution in terms of economic efficiency is to operate each system at a point where marginal benefits of leakage control exactly equal marginal costs. If the marginal benefit were greater than marginal cost, more resources should be allocated to the system to reap those benefits. If, on the other hand, the marginal benefit were less than marginal cost, i.e., each additional unit of resources were actually producing less benefit than it is worth, then those resources should be transferred elsewhere. At the point where marginal benefit equals marginal cost, the total net benefit is greatest (as long as total benefits are greater than total costs).

Hanke then goes on to give a numerical example by applying this decision rule to data from Perth, Australia. The formula he gives for marginal cost (except for what appears to be a typographical error) corresponds to the "average incremental cost" mentioned earlier, described by Saunders et al. (1977) in their World Bank paper, and used by the British NWC. The planning horizon used in his formula (with no explanation or justification) is five years.

The analysis is straightforward until the point where Hanke introduces numerical values for the respective changes in benefits and costs that would result from the two policies under consideration. To estimate benefits, he gives the level to which system leakage would be reduced for each option (7.5% of total production for the first, 5% for the second). To estimate costs, he states his assumption of the resources required for each option; one "waste prevention worker" (detecting and repairing leaks) per 10,000 dwellings for the first option, one waste prevention worker per 7,500 dwellings for the second. He gives no justification, however, for these figures, which imply a known relationship between leakage level and number of leak detection personnel. The British were able to predict the leakage level corresponding to a certain leakage control procedure only because of their years of field observations. Without an extensive data bank such as this, it is impossible to predict accurately the effect of a given leakage control program. This type of data may have been collected for Perth (although Hanke does not tell us so), but for any system without such records, this marginal cost analysis cannot be used. Nor can it be used when future expansions are not planned out, because the true marginal cost of the water cannot be calculated.

5.2.4 Predictive models

In recent years, there have been several attempts to develop predictive models for main break rates, based either on the system characteristics or the history of past breaks. Although these models were not developed in the context of leakage control, but were meant rather to aid in decisions on main replacement in large cities, they are of some interest here. Research is ongoing to refine these models.

5.2.4.1 Models based on historical records

Shamir and Howard published the first model for predicting main breaks, in 1979. Their model was an exponential one, with time the only variable. Their equation was of the form $N(t) = N_o e^{At}$ where N(t) is the number of breaks per 1000-foot length of pipe in the year t, and A, the growth rate parameter for main breaks that is determined from historical data. (Shamir & Howard, 1979, pp. 252, 254)

5.2.4.2 Models based on physical system characteristics

In 1982, Walski and Pelliccia published a model that combined Shamir and Howard's historical model with some physical characteristics of the system, by developing different equations (all of the form $N(t) = N_o e^{At}$) for different types of pipe material, different diameters, and different break histories (i.e., no previous break, one or more previous breaks).

Clark et al. at the U.S. Environmental Protection Agency (EPA) published another model for main breaks based on physical system characteristics and historical records (Clark et al., 1983). They used regression models to predict (for individual pipes): 1) time to first break, and 2) total number of breaks as a function of time since the first break. Both equations included physical system characteristics (such as pipe material, diameter, pressures, traffic loading, soil characteristics) as the independent variables.

Since 1982, Clark's team has been revising its work, and in a June 1985 draft focused on probabilistic rather than deterministic prediction models. The report also presented regression equations for breaks/mile as a function of the same system characteristics listed above (with the addition of wall thickness), one equation for each of the two large utilities studies.

5.3 Leak reduction/case studies in developing countries

As stated earlier, the approach to leakage control taken by large cities in developing countries has generally been to hire outside consultants, who do either a complete detection search with sonic equipment and occasionally noise correlators, or perform some type of water audit followed by sounding. There is usually no economic analysis performed, either on what the optimum leakage level might be, or on the actual benefit/cost ratio of the entire detection and repair process. In fact, costs are rarely reported. One exception to this is a large study of unaccounted-for water carried out in Bangkok, which is discussed in section 5.3.3.

5.3.1 Libreville

One typical example of a water study in a developing country is that done in Libreville, Gabon, where a French consulting firm was called in when the ratio of water sold to water produced dropped from about 70 - 80% down to 57%. Courteau and Moser (1979) report on the three-month sounding program carried out by the French company SAFEGE. They give the number of leaks found and the volume of leakage recovered.

As a result of the survey, 10% of the total production in the area they surveyed was recovered. They felt that was not enough, and went on to check connections and meters, at which point they found that 35% of the meters were not being read because they were broken or not accessible. It was then felt that a general inventory of the system was necessary, so SAFEGE (always in conjunction with the national water and electricity board) proceeded to draw up a map of the entire system in Libreville, a city of 180,000. They mapped the distribution systems of both the water and electricity networks in a total of 21 months, including 10 months in the field. The last stage of the project was to inventory all the meters and consumption points for both the water and electric services, which took another six months.

Nowhere in this article were the costs mentioned, nor the benefits. The leak detection program was initiated because of the sudden increase in unaccounted-for water, and the consultants' approach was to survey one area of the city by sounding to see if leakage was the main problem.

5.3.2 Sao Paulo

Another water study, this one aimed specifically at reducing leakage, is the "RMSP Special Losses Reduction Program" carried out in Sao Paulo, Brazil from 1978 to 1983. Riomey *et al*. (1982) report on the background, methods, and results of this program, but do not include any economic analysis, other than showing that at the present level of production, each 1% reduction in loss is equivalent to a savings of 11 million m^3 per year, which corresponds to about 3 million dollars a year. Given an expected increase in production, they predict that by 1987 1% of the production would be worth 4.5 million dollars a year.

Using percent of production as their unit of measurement, an arbitrary goal was adopted: to decrease unaccounted-for water from its level of 38% in 1978, to 20% by the end of 1983. By 1981, however, the "index of losses" (presumably the same index as used for unaccounted-for water) had only decreased to 30%. The authors do not give the cost of the efforts required.

5.3.3 Bangkok

As mentioned above, the water study done in Bangkok (CDM-MEC, 1983) provides an exception to the general lack of economic analysis in water studies in developing countries. Camp Dresser & McKee, Inc. (CDM), in conjunction with Metropolitan Engineering Consultants Co., Ltd. (MEC), carried out an extensive study of unaccounted-for water, in the context of an overall project to implement mainlaying, operational and maintenance programs for the Metropolitan Water Works Authority of Bangkok. The consultants were responsible only for analyzing the different components of unaccounted-for water and not implementing a loss reduction program, but they did make recommendations for future leakage reduction programs. Unaccounted-for water was defined as unbilled water.

Two programs are considered for leakage reduction in the CDM-MEC report: 1) the wrapping of galvanized steel service mains and connections with polyethylene sheet, and 2) treatment of the delivered water to correct its corrosiveness, both for well water and surface water (75% of service connections and almost all service mains are of galvanized steel -- p. S/2).

Benefit/cost ratios are calculated for each of these programs, which "required assumptions to be made about the relative importance of service main and service connection deterioration and about the relative impacts of internal and external corrosion" (p. S/8). The analysis is detailed and the assumptions numerous; after varying all the assumptions in a sensitivity analysis, the final conclusion is that wrapping of new and replacement galvanized steel service mains and connections with polyethylene "is economically justified, and the benefits are so high and the cost so low as to give this measure a very high priority" (p. S/8).

This analysis includes, of necessity, an estimate of the value of water saved, which is in itself a complex calculation. The assumption is made that any leakage recovered can always be sold, and that the value of water saved, therefore, cannot be less than the current marginal sale price. However, if the cost of water production exceeds the price, then the value of the water saved is equal to the cost of production. The possibility of deferring future expansions is examined; and costs of the distribution system upstream of a leak are considered part of the cost of the leak. All scenarios are examined at several different discount rates. (See CDM-MEC, 1983, pp. 6/1 to 6/7.)

Although the CDM-MEC report gives recommendations for long-term leakage reduction through replacement and wrapping of galvanized steel piping, the authors felt that location of the extensive underground leakage is impossible "under conditions prevailing in the Bangkok water distribution system" at the time of the report. "Major efforts are needed in upgrading distribution mapping and valving, and system pressures must be increased, before any effective program for locating underground leakage can proceed" (p. S/10).

Intensive studies were carried out in five small isolated areas of the distribution system, to assess customer metering, leakage, waste and illegal water use.

These areas were chosen for their "high" pressure (to facilitate underground leak location by sounding), and the ability to isolate these areas from the system (for flow measurements) (p. 4/12). Even in these areas, leak detection was made difficult by the fact that 12% of all pipelines were inaccessible (private homes had been built over many of them).

It is of interest that the pressure was about 3 to 9 meters in each of the five zones -- this should be compared to the absolute minimum of 7 meters considered necessary by Heath Consultants for sounding programs (cf. section 4.4). The leakage detected in the five zones was 14% of the total production. The 10% of total production which remained unexplained after the other components of unaccounted-for water had been assessed (meter under-registration, illegal use, etc.) may be due in large part to underground leakage that could not be detected because of the low pressures.

The report recommends a five-year program of leak detection, repairs, and mains replacement (see p. 8/2), in which the first two years must be spent in upgrading distribution mapping and valving, and eventually raising system pressures to permit leak detection. The authors feel that a feasible five-year goal is to reduce leakage from about 36% of total production down to 20% (p. 5/11).

5.3.4 Small systems

Unfortunately, the experiences of large cities, such as those mentioned in the three case studies above, do not have much to offer the managers of small systems in terms of recommendations on where and when to carry out leakage detection efforts. Nor can the same methods be adopted -- the detailed analyses in Bangkok, for example, relied not only on the services of an outside consultant, but also on the existence of plans for future capacity expansions.

What can be generalized, however, is the importance of mapping the distribution system, and also the importance (mentioned earlier) of a minimum system pressure in order to carry out sounding.

5.4 Priority-setting for leakage control

Experience has shown that a small number of pipes are responsible for the majority of breaks in a system; in other words, that pipes that have broken before are much more likely to break again (e.g., Reed [1980], O'Day [1981], World Water [1984], Clark *et al*. [1985]). This point is stressed throughout the literature; in addition, it is pointed out that among those pipes that break, a small number of the leaks are responsible for the majority of the total leakage volume. A number of authors therefore point out, either explicitly or implicitly, the importance of identifying the areas with the highest leakage levels when carrying out a leakage reduction program.

Pilzer (1981, p. 567), when discussing the type and level of leak detection program that would be most economical or practical, states, "A beginning can be made with a modest overall study to determine where pinpoint leak detection would be most productive. After this overall investigation or review from leak records, pipeline corrosion records, knowledge of soil conditions or regional surveys, specific areas can be identified for closer scrutiny." Mulekar (1983) repeats this statement.

Lilley (1984) reports a case where three different zones of a city were chosen for a leak detection effort, to try to identify the factors responsible for high levels of leakage (high ground water, old pipes, etc.). Implicit in this approach is the idea that leak detection efforts will be carried out in areas with characteristics similar to those of the pilot zones with the highest levels. (Data from these three zones are presented in Table 2, and discussed in section 3.6.3.2[c].)

The Office of Water Resources in North Carolina has set up a numerical point system to establish priorities in aiding systems that have requested assistance from the state leak detection team. The form is shown in Exhibit 1. This differs from the cases above, in that priorities are established not just based on high rates of leakage - for instance, small communities are given priority over large communities.

The issue of setting priorities, and of locating those portions of a system that have the highest leakage rates, is an important one, and will form the basis for our policy in Chapter 6.

5.5 Value of water

Calculation of the economic benefits to be gained by any given leakage control policy must include the value of the water saved. There is no agreement in the literature on how to calculate this value. We have mentioned several approaches taken: the NWC (1980) and Hanke (1981) both recommend using the marginal cost (defined as average incremental cost) of water; Moyer et al. (1982) value lost water at the purchase price plus average power and chemical costs; and CDM-MEC (1983) takes the value of water to be the retail price or the "cost of production" (including future expansions), whichever is higher.

In theory, the marginal cost of water is the best expression of the true value of water (assuming it is feasible for the water authority to increase production). In practice, there are many problems in calculating the marginal cost of water supplies. These are largely due to the "lumpiness" (non-continuity) of the relationship between system capacity and cost. In other words, the immediate cost of producing an extra unit of water is very low when the system is not used to full capacity; this cost suddenly jumps to a very high figure when there is no excess capacity and a new plant (or reservoir or distribution system) must be built to provide additional water. Saunders et al. (1977) describes four different definitions of marginal cost used in the water supply sector, several of which use averaging techniques to smooth out the marginal cost. Mann and Schlenger (1982, p. 7) discuss the computational problems associated with calculating marginal costs.

Given the complexity of calculating marginal costs, many engineers revert to using the current (unit) cost of production as an expression of the (unit) value of water. The tendency is often to consider only the annual operating and maintenance costs, but this seriously undervalues water. The initial capital investment must be accounted for as well. This can be done by including the opportunity cost (or interest) on the capital, and the depreciation of the capital itself, in the total cost of production. The rationale for using current cost of production as the value of water is the assumption that water will cost roughly the same to provide in the future as it did in the past. That is not always true, however, and therefore cost of production may be a very poor approximation of marginal costs. It may also be difficult to calculate, especially when the historical costs of the system are not known - as is often the case in developing countries. The replacement cost (or cost to reconstruct the same system today) can therefore be used instead of the actual historical capital cost of the system in calculating the current cost of production. Even so, the replacement cost of an existing water system may be very different from the cost to develop another source, which may be much less accessible.

The marginal cost (as approximated by average incremental cost) of water is therefore the best estimate of the value of water. In developing countries with few historical records, it may also be no more complex to calculate than the true current cost of production. (It should be noted that these expressions of the value of water only measure the cost (either past or future) of producing water, and cannot provide any indication of the health benefits to be gained by increased water service or reduced contamination. The average incremental cost is therefore only a lower bound on the value of water to society as a whole.)

6. TOWARD A LEAKAGE CONTROL POLICY IN DEVELOPING COUNTRIES

6.1 Setting and assumptions

As stated before, we are concerned with existing small and medium-sized water distribution systems in developing countries, those that do not have the resources to hire outside leakage specialists. Not only do they lack resources; the managers of those systems often lack an awareness of the leakage problem or how to tackle it. These systems usually have trouble covering their recurrent costs (operation and maintenance).

We are assuming, then, that a national government agency or regional authority of some type with responsibility for these systems must be established. This agency will (and should) be in charge of conducting leakage control activities, as well as providing other services. This agency will determine which systems would benefit from a control program, allocate resources accordingly, and provide technical assistance and guidance to those utilities. Many of the decisions to be made about allocation of resources among different systems will parallel decisions to be made about resource allocation among the different portions of a water system.

We are assuming as well that little or no records exist on the distribution networks of these water systems, that there are few valves, that there is little or no metering, and that consumers are often forced to draw water at night because of the relatively low pressures during the day. Because of this, waste metering, which relies on careful operation of valves throughout the system and on measurement of minimum night flows, will not be a viable option for leakage control. District metering may be possible in some areas, especially since small systems often tend to have branched rather than looped networks and therefore flow to different portions of the system can be measured separately. District metering, however, requires installation of meters, regular reading of those meters, and comparison of flows over time. And when district metering is practiced, it is always followed by sounding in areas of high flow. Sounding, therefore, remains the basic method of leakage control available. We consider district metering to be a potential method of setting priorities for sounding programs, and consider sounding the one viable method of active leakage control for small systems in developing countries.

We are also assuming that most of these systems have no detailed plans for future expansion.

Our final assumption, one that is important in the calculation of the cost of leakage (or value of water recovered) is that demand exceeds supply - that many consumers would use more water if available. This is usually true where there is intermittent supply, or very low pressure. There is almost always an unserved population in the area as well, that would like to be supplied with water.

A final assumption is that most of the systems described above have considerable leakage, at least in some portions of the system. Accordingly, a policy is needed for leakage control under the circumstances described above.

6.2 Theoretical approach

Theoretically, the optimal policy for any water system would be to practice leakage control at a point where the marginal benefits equal the marginal costs of the control program, as discussed in section 5.2.3.1.

When there is a budget constraint, however, which is most certainly the case in the water systems considered here, the optimum may not be possible. The ideal approach under these circumstances is to allocate the scarce resources in such a way that the ratio of marginal benefits to marginal costs is the same for all systems. In terms of leakage control, this would mean carrying out each program at a level where the ratio of marginal benefit (the value of the additional increment of water saved by the next unit of "control effort") to the marginal cost (the cost of that increment of leakage control effort) is the same for all systems. At the same time, the total expenditures must not exceed the budget constraint. If the ratios were not all equal, one unit of "detection effort" could be transferred from a system with a low ratio to a system with a higher benefit-cost ratio and produce a higher benefit.

There are serious problems with putting this approach into practice, however. The marginal benefit of leakage reduction (value of water) is difficult to calculate, as discussed earlier, but the marginal cost of one unit of leakage control effort cannot really even be defined. There is no "unit" of leakage control effort. There are several discrete methods of leakage control, each with a cost associated with it. These costs vary somewhat with the size and material of the main, but are fairly constant for any given system. Increasing the level of leakage control usually entails adopting a different, more stringent control method, with a higher cost. So the benefit-cost "curve" for leakage control methods really consists of several discrete points, one for each method of control.

In addition, as discussed in section 6.1, there are really only two methods of leakage control under consideration here: passive control and sounding. And given that almost all systems practice passive control, the choice facing the decision-makers is not which of several actions to choose, but rather whether to take an action or not. Rather than choosing a point where $dB = dC$ (marginal benefit is equal to marginal cost), the question is whether $\Delta B > \Delta C$ (total [change in] benefits is greater than total [change in] cost), for each system.

6.3 Practical approach

The issue, then, is how to allocate resources among a number of water systems with different anticipated benefit-cost ratios for leakage detection. The obvious solution in terms of economic efficiency is to carry out leakage detection first in the area with the highest benefit-cost ratio, and continue for decreasing benefit-cost ratios until either 1) there are no more systems with a benefit-cost ratio greater than 1, or 2) there are no more funds available for leakage control. The same procedure would apply in determining which portions of a water system to survey.

We are assuming here a one-time leakage detection program. The question will arise of whether to repeat leakage detection in zones with high initial benefit-cost ratios or to proceed to other zones. We will return to this question later.

We are following the general idea brought up in section 5.4, that of setting priorities: carrying out leakage detection first where it will have the greatest impact. What we need, then, is some way to establish quantitatively the relative effects of leakage detection in different areas, so as to choose the one with the highest benefit-cost ratio.

6.4 Information needed

The two main pieces of information required for the decision process are the cost of the leakage detection and repair program, on the one hand, (ΔC), and the benefits gained from the leakage reduction, on the other (ΔB).

The only volume of water that concerns us, then, is the amount of leakage that will be found and repaired due to the detection program, and not (as required in the British procedure) the total volume of leakage in a system. This is a very important point, and means that overall leakage (Step [a] in the NWC procedure) need not be measured.

Four specific types of information are needed to determine ΔC and ΔB: 1) the unit cost of the sounding program and of repairs, 2) the number of leaks, 3) the unit value of the water recovered, and 4) the amount of leakage expected to be discovered during the detection survey. Number and volume of leaks (items 2 and 4) are discussed together.

6.5 Generating the information

6.5.1 Costs of detection and repair

There are actually two separate components to this, the cost of detection, which is fairly constant per mile of main, and the cost of repairs, which varies with the number and type of leaks found. Many authors report the two together, however.

The costs of detection and repair are different in developing countries than they are in the industrialized countries. Labor (the main component of detection and repair costs in the industrialized countries) is much cheaper in developing countries, and equipment may be more expensive, especially if it is imported. No data were found in the literature for leak detection costs in developing countries.

The cost of detection surveys is determined by the time required to perform the sounding (see section 4.5) and the appropriate labor cost. Typical costs in the U.S. are about $200/mile of main.

Table 5 shows the variation of repair costs for different sizes of (ductile iron) pipe in a U.S. water system. Walski & Pelliccia (1982, p. 142) state that "pipe repair costs are not available from standard sources," and therefore they synthesized these data with assistance from the Binghamton water distribution department. It is interesting to note that the crew is by far the largest component of the cost in every case except for the largest pipe shown (600 mm). These costs cannot be expected to apply to the water systems considered in this paper, but the table is an example of how repair costs can be generated from a reasoned estimate of their components. The authors give a brief explanation of how each component was calculated.

Table 6 shows the average unit costs and benefits of leakage detection and repair by type of leak, for a series of three surveys in Mamaroneck, N.Y. (The "other" category represents leaks found on other utilities.) Costs included labor, pavement, materials, detection (apportioned equally among all leaks) and overhead. Leaks were detected by sounding. The average cost per leak for all categories in Table 6 is $480; this ranged from $423 to $541 over the course of the three surveys. (Moyer et al., 1982, pp. 356-364) By comparison, Pilzer (1981, p. 566) reports a cost of $325 per leak (1976 dollars) for location, repair, materials, and right-of-way restoration in Gary, Indiana. In this case leak location was also carried out only by soundings.

As stated before, costs will be quite different in developing countries. No data are currently available, but costs can be synthesized (as in Table 5) for the particular conditions of any region. Cost data should also be collected as leak detection surveys are carried out. We will return to this point.

As in Table 5, the costs in Table 6 are not expected to apply to systems in developing countries. It is interesting, nonetheless, to note the variation in costs in detection and repair among the different types of leak. Unfortunately, this table does not show valve and joint leaks separately.

6.5.2 Unit value of water

In a system where demand exceeds supply, the best estimate of the economic value of recovered water is the cost of producing that additional water by other means, or the "average incremental cost." As discussed in section 5.5, for developing countries with few records, calculating average incremental cost may be no more difficult than calculating the current cost of production. Although few countries have as complete a future plan for the water supply sector as do the British, there is always some knowledge of the approximate cost of new production. This information is not available at the level of individual small utilities, but could be calculated by the type of centralized water authority that is necessary for a national leakage control policy and for improved overall management of the water supply sector.

Average incremental cost is usually calculated for an entire water system. Because we are trying to prioritize the need for leak detection in different zones of an individual system, however, the value of water should be looked at separately for each zone if possible. This is especially important if some zones are at a much higher elevation than others, and therefore incur additional pumping costs.

6.5.3 Number and volume of leaks

Central to the choice of those systems or portions of systems which will benefit most from leakage detection is knowledge of the amount of leakage that will be discovered, both in number and volume. Ideally, this should be predicted before beginning the leakage detection program, to find the areas with the highest expected benefit-cost ratio for leakage detection and repair.

The British were able to predict the level of leakage to be expected under different control methods only because of their years of collecting data from water systems that practiced those different control methods. Because there are so few historical records of any kind on water systems in developing countries, we hoped at one point in our research to build a model for predicting leakage that would be based on physical characteristics of water systems, such as the one developed by Clark *et al.*, discussed in Section 5.2.4.2. As we will show in section 6.5.3.1, this turned out not to be practicable.

Because the amount of leakage found during a detection program cannot be predicted for the small water systems considered here, it will have to be measured. The only solution is to begin leakage detection programs (in areas where high leakage is expected) and to begin keeping records of the actual amount of leakage discovered and the actual detection and repair costs, to determine if the detection program is economically viable ($\Delta B > \Delta C$) and whether it should be extended to other areas. The goal is still to carry out detection efforts in the area with the highest benefit/cost ratios first, so some method of prioritizing the areas is needed. This is discussed in detail, in section 6.6.

6.5.3.1 Problems with applying predictive models to developing countries

Of the various predictive models described in section 5.2.4, the only one apparently suitable for our needs was the 1985 work of Clark *et al*. at EPA. The model predicts breaks/mile, and equations for volume/mile could conceivably be developed along the same lines.

As mentioned in section 6.5.3, we had originally hoped to use Clark *et al*.'s data to build a prototype predictive model for leakage prediction in developing country systems, and use this model, through simulation, to assess the relative importance of different system characteristics. After spending some time in Cincinnati with members of the EPA team, we concluded that this was not feasible, for reasons listed below:

a) Clark *et al*. (personal communication) do not believe this type of equation is transferable from one system to another. One major reason for this is the difference in maintenance policies between different systems. This factor is not captured in the physical parameters of the equation but definitely affects the overall level of leakage. Different cities have different policies with respect to pipe replacement, to pipe cleaning and lining, to corrosion protection, and to leak detection practices and frequency. (Clark et al. had no data on the leakage control policies of these cities, so it remains unclear whether the equations are predicting those leaks that surface under passive control, or also leaks found by active detection.) Clark et al. also feel that quality of construction is a very important factor in determining breaks, especially the first break in a given pipe.

In some developing countries, there may be less variation in maintenance policies between systems. There will be some variation, however, especially in the elusive "quality of construction" factor. In addition, there are more immediate obstacles to adapting the EPA model:

b) Clark et al. developed their models for an entirely different range of parameters than those applicable to small systems in developing countries. Because the purpose of their model (and the others in section 5.2.4) was to predict future breaks in large mains in order to establish a main replacement policy, their dataset consisted only of pipes 6 inches and larger. They state that there is a distinctly different breakage pattern for smaller pipes (small pipes break more often). In the developing country settings of interest in this analysis, most of the pipe is considerably smaller. Also, Clark et al.'s data are only for metallic pipes, and completely different relationships can be expected for the asbestos-cement and plastic pipe commonly found in developing countries.

Completely new regression equations would have to be developed, then, for any country under study. This would take years of data collection, and the final result would still suffer from the limitations discussed in point (a) above. This approach is clearly not what is needed to address current leakage problems in developing countries.

6.5.3.2 Collecting leakage data through detection programs

As suggested in section 6.5.3, the only practical method to obtain realistic data on number and volume of leaks found through leakage detection programs is to begin those programs and keep track of the results. Records must also be kept of the actual detection and repair costs.

As mentioned in section 6.3, we still need some quantitative measure to use in establishing priorities. Rather than the actual value of water that will be saved through leakage detection, something that we cannot predict before beginning the program, we suggest instead an index based on the leakage found under passive control. We are making the important and reasonable (Bays, 1984, p. 53) initial assumption that areas with high surface leakage also have high underground leakage. Repair records must be kept for several months by the operators to establish the "hotspots" in the system. Mapping of the distribution system should also begin. This may be a complex task in many cases, but it is necessary for the long-term management of the system. In fact, leakage detection can contribute to the mapping effort, because information will be gathered on location of pipes and valves.

6.6 The procedure

In the context of a single water system, the general procedure is as follows: the areas with the highest leakage rates are identified from the repair records. At the same time, the marginal cost of water is estimated, and the pumping costs for the different zones, if that has not been done before. The regional leakage detection crew comes in to begin a sounding program in the zones with the highest expected return per unit of expenditure, based on a priority index that includes 1) the level of leakage under passive control, 2) the value of the water, as measured by the cost of production, and 3) the expected cost of detection and repair. (Again, we are assuming that areas with high surface leakage will have high underground leakage -- this is the basis for using this index to establish priorities.)

Sounding is done throughout the whole zone, and the actual ΔB and ΔC of the leak detection effort are calculated. The sounding crew then investigates the zone with the next highest priority index, and so on. If (as expected) it emerges at some point that the leakage detection program is no longer economically worthwhile, it should be suspended.

There is no way of knowing *a priori* the volume of leakage that will be detected during the very first leak detection survey in a given water system. There is, however, a high probability that a small water system in a developing country, with no previous active leak-detection effort, will have extensive underground leakage somewhere in the system. With a regional leakage detection crew, the costs of a detection survey will be greatly reduced for each individual water system. We therefore believe that leakage detection should always be carried out at least in the zone where the highest benefits were expected (based on the priority index), and that it will rarely be uneconomical. If it is ever found that the leakage recovered in the zone with the highest priority index did not justify the costs of the leakage survey, the remaining zones of that system are not surveyed.

6.6.1 Decisions to be made

There are a number of management decisions that cannot be made here, but that will have a bearing on any leakage detection program. We would like to touch upon these issues and explain their relevance before proceeding to a hypothetical case study.

Issue 1: When dealing with a single system, how many zones, of what size, should the water system be divided into? How should they be defined? Should they be defined only after repair data has been collected?

One possible approach is to have zones of approximately equal size -- either equal geographic area or, more logically, equal lengths of pipe or equal numbers of connections. This would give a good basis for comparison between zones, and would also mean that a leakage detection survey would take roughly the same amount of time in each zone. We feel, however, that it is more important to define the zones in terms of those characteristics that will affect the leakage level or expected benefits.

Since the benefits of reduced leakage depend in large part on the value of the water saved, zones should be defined in terms of the costs of producing water in each area. If the topography of the served area is such that water must be pumped to some areas, those areas should be set aside as having a higher cost of production, and therefore a higher benefit from a given amount of leakage reduction, than a zone fed only with gravity flow.

If the distribution system is divided into areas served by different reservoirs, or otherwise isolated, the leak detection zones should be divided along those lines as well. If at some point district metering is undertaken, the flow into each of these zones can be monitored separately to watch for any sudden increases.

If there are system characteristics that vary widely across the water system, it might be desirable to define the zones along those lines as well (different soils, pressures, pipe types or age, standposts vs. house connections, etc.).

Finally, if the repair records collected under passive control show a high rate of repairs in some localized area, that area should be a separate zone (or zones) for leak detection purposes, even if it was not identified in any other way. The high rate of repairs may be due to quality of construction or some other factor that is not immediately obvious.

There should be some minimum zone size, based perhaps on the amount of distribution system that could be surveyed by a crew in one day.

Issue 2: How should the repair rates be classified? Is an average of 8 leaks/km significantly different from 7, or 20 m^3/day/km significantly different from 25 m^3/day/km? The selection of repair rate levels (5 - 10 leaks/km, for instance) will have to be based on the range of values collected. For the leakage volumes, it will also be based on the precision of the volume estimates.

Issue 3: How long must repair data be collected under passive control before average rates can be assigned to each zone, to prioritize them for purposes of active leak detection? The more historical data available, the more representative the averages will be of the true situation.

There may also be seasonal trends in the repair pattern that would not be detected if data were only collected over a few months. On the other hand, the longer the utility waits before beginning leak detection, the more water is lost. In general, the managers of a water system will have some idea of the hotspots in the system. What is needed, however, is some quantitative measure of the leakage levels in each water system for purposes of comparison. A minimum of several months of data is therefore recommended.

Issue 4: How many leakage detection teams should be trained for a given area of the country? And will some (relatively) large systems warrant having their own leak detection crews? This question may best be answered after the first leak detection has been carried out in several systems.

6.6.2 Numerical example

Assuming that the zones have been defined and the leakage levels under passive control recorded, we illustrate the procedure for carrying out active leakage detection, using the hypothetical data in Table 7 to establish priorities among the different zones.

The first row of figures, Vp_i, gives a measure of the volume (V) of leaks found and repaired under passive control (P) in each zone (i). As the leaks are only repaired after they surface, the repairs are spread out over time. This figure is a sum of all the leakage rates found during a certain time period, and does not represent the amount of leakage at any one point in time.

The second item, Np_i, is the number of leaks found over the same time period (and, of course, over the same length of distribution mains). If possible, the same time period of observation should be used for each zone to enable comparison of the figures.

W_i is the value of water for each zone i. In the case shown here, the basic average incremental cost of water production (zones A and D) is $\$.15/m^3$. Zones B, C and E show higher costs because pumping is required for those zones. Four different levels of cost are shown here, for purposes of illustration, but many small systems may only have one or two different costs of water production throughout their system.

An index, P_i, is then calculated for each zone i (see Table 8), where P_i is the ratio of (leakage rate) x (value of water) to (number of leaks) x (repair cost per leak). If it is reasonable to assume the same average cost per repair in all zones, a simplified index can be calculated: $P_i' =$ (leak rate) x (value) / (number of leaks).

It is important to realize that this index has no real physical meaning. It is not a benefit/cost ratio of the repairs done under passive control; such a calculation would have to incorporate the time over which each leak remains unrepaired, to get the total volume lost. This index, P_i

(or P_i') is only a rough guide as to which zones would benefit most from an active leakage detection program. Leak detection is begun in the zone with the highest index P_i, on the assumption that the leaks found during the leak detection survey will be proportional to the leaks that surface during passive control, both in number and volume. This is just to provide a starting point; as the leakage detection surveys are carried out, that assumption will be checked, and any necessary modifications made.

Note that including the value of the water gives a different priority than one might assume from the leakage rates alone. Zone A in Table 7 has the highest leakage rate of the five zones, but because no pumping is required, a leak detection program in that zone is not expected to be as beneficial as in some of the zones that require pumping. In fact, zone A is fourth on the priority list in Table 8.

The leak detection crew will begin in zone B, then, the zone with the highest index, and survey the whole of zone B. When the detected leaks have been repaired, the benefit/cost ratio ($\Delta B/\Delta C$) for active leakage detection and repair in zone B is calculated. (We will discuss this calculation in section 6.6.3.) If the benefit/cost ratio is greater than 1 (benefits greater than cost), the crew will move on to the zone with the second highest priority index, or zone C in this case, and proceed in the same manner as for zone B.

Eventually, it is expected that the costs of leak detection and repair will exceed the benefits in some zone. If the difference is great, the detection crew may choose to stop there. If the benefits are almost as great as the costs, however, the crew may choose to investigate one more zone -- especially if the priority indices of the two zones were similar. For example (see Table 8), if after carrying out leak detection and repair in zone E it were discovered that the costs were slightly greater than the benefits, it might well be decided to continue to zone A, which had a priority index very close to that of zone E. If the costs were greater than the benefits for zone A as well, zone D would probably not be investigated.

If the benefit (as measured by the cost of water) is fairly close to the cost of the program, it might still be judged a beneficial program. As mentioned in section 5.5, the value of water used here does not include benefits to consumers such as health improvements. Those effects are not usually considered by individual utilities, but a regional authority should have a wider perspective on the implications to society as a whole of reducing leakage.

When sounding the first zone of a water system, as stated before, there is no way of predicting the amount of underground leakage that will be detected. Over time, however, a pattern may emerge, with the benefits of active detection roughly proportional to the priority index. This will be of aid in deciding whether to continue leak detection in subsequent zones. It is also possible that no such relationship will emerge.

As mentioned earlier, a decision will have to be made at some point whether to continue to a new zone or repeat the leakage detection survey in a zone that proved to have high leakage in a previous survey. This will have to be an arbitrary decision at least until enough data is gathered on repeat surveys to determine the relationship (if any) between the amount of leakage found on the first survey and on subsequent surveys. Based on the literature, however, we suggest that a repeat survey not be carried out any earlier than one year after the first survey. It is expected that less leakage will be found on repeat surveys than on the initial one, and if too little time has elapsed, the newly occurred leakage will not warrant a detection effort.

It is important to emphasize that this is an iterative procedure, and that data should be kept on all leak detection surveys to guide future leak detection. In a sense, the idea of going ahead with detection efforts because leakage is expected is similar to the approach taken by most small systems in the U.S. We are trying to establish the importance of actually evaluating the benefits of such detection programs, and of prioritizing detection efforts. This should theoretically be done everywhere, but it is especially important in developing countries, where resources are so limited.

The procedure has been described here for different zones of a single system. The same approach applies for establishing priorities among the different water systems for which a regional leak detection crew is responsible.

6.6.3 Calculation of benefit/cost ratio of active leak detection and repair

After active leak detection and repair has been carried out, actual data will be available on the costs of the effort and the amount of leakage recovered (expressed as a rate: volume/time). To calculate the economic benefit of recovering leakage, however, it is necessary to know how long the leak would have continued undetected (before surfacing, or being detected by a later detection survey), to calculate the total volume of water "saved." As discussed in section 5.2.3.1, there is no satisfactory answer to this question. A logical argument for a regular sounding program is that made by Moyer et al. (1983), that the average lifetime of underground leaks is one-half the time between surveys (assuming that new leaks occur at a fairly constant rate over time). In our case, however, the time until the next survey is not known.

What we suggest, therefore is a sensitivity analysis: calculation of the benefit/cost ratio for several different assumed lifetimes of the leaks, from one year to fifteen years. If it is found that the benefit of the recovered leakage would exceed the costs even if the leaks had only continued for a year, it can be assumed that the program is economically justified. If, on the other hand, it is found that the benefits would exceed the costs only for some exceedingly long lifetime of the leaks (say, fifteen years), it can be concluded that the leak detection and repair effort was not economically justified. It is not reasonable to assume that the situation would remain unchanged for so long -- the leaks might grow to the point where they surface or disrupt service, and are then discovered and repaired; another leak survey would probably be carried out in that time; and the system might well be extended or modified during that time. Finally, if it is found that the benefits would exceed the costs only if the leaks were to continue undetected for some intermediate length such as 8 years, a decision must be made as to whether that is a reasonable expectation. This is when the nonquantifiable benefits of leakage must be taken into account as well to decide if that particular leak survey was justified and whether the crew should continue on to the next zone.

In all these calculations, the benefit should be calculated as the net present value of the total volume of recovered water. This is calculated by discounting the value of the water that would have been lost each year back to the present, and summing the discounted benefits from each year the leak was assumed to persist (if it had not been detected and repaired in this survey).

As an example, using the value of water for zone B in Table 7, and values for average leakage rate per leak and average detection and repair costs adapted freely from the data of Moyer et al. (1982): If after sounding for leaks in zone B, 30 leaks were discovered with a total estimated leakage rate of 750 m^3/day, with a total cost of $7,000 to detect and repair those leaks, the benefit/cost analysis would be performed as follows:

annual value of recovered water =

$$750 \text{ m}^3/\text{day} \times 365 \text{ days/yr} \times .18 \ \$/\text{m}^3 = 49{,}300 \ \$/\text{yr}$$

No sensitivity analysis is needed in this case; even if we had prevented the leaks for only one year, the benefits ($49,300) would far exceed the costs of the detection and repair ($7,000).

To take another example, if only 20 leaks were discovered with a total leakage rate of 200 m^3/day, and a cost of $15,000 to detect and repair, the calculation would be as follows:

annual value of recovered water =

$$200 \text{ m}^3/\text{day} \times 365 \text{ days/yr} \times .18 \ \$/\text{m}^3 = \$13{,}140$$

This is slightly less than the cost of $15,000 to find and repair those leaks. At an assumed discount rate of 10%, and an assumed lifetime of two years, the net present value would be $13{,}100 + (13{,}100 \div 1.1) = \$25{,}000$. The net present value of the recovered leakage ($25,000) would exceed the costs ($15,000) if the leaks are expected to last an average of two years -- which would be the case if the zone were to be surveyed four years later. However, even if the leaks were expected to last only one year in the absence of this survey, the recovered value of $13,140 is so close to $15,000 that the survey should be considered a success (given the non-quantifiable benefits of 20 fewer leaks in the system and 200 m^3 more water available per day for customers).

As the leak detection efforts get underway and data is collected, a decision should be made on the timing of repeat surveys. This is not addressed here.

6.6.4 Limitations of the procedure

This procedure is offered only as a suggestion for those systems where there is some basic knowledge of the distribution system and where the system pressures are high enough to allow sounding. It is an unfortunate reality that active leak detection can not be carried out in areas where the pressure is too low to permit sounding, and where not enough is known about the system to safely boost up the pressure for the detection survey. (There are other techniques that do not rely on the intensity of the leak sound but, as argued before, these are too expensive for the small systems considered here.)

It should be noted that leak detection can be carried out at pressures lower than those recommended by American and European firms (as evidenced by the CDM-MEC study in

Bangkok -- see section 5.3.3). Some leaks will remain undetected, but if enough leakage is recovered to justify the costs of the program, the total amount of leakage is irrelevant.

6.7 Summary

The leakage problem is just one manifestation of the general inadequacy of maintenance in water systems in developing countries, which in turn is a result of overall management problems: lack of institutional support, shortage of skilled personnel, shortage of funds. As such, leakage control cannot be fully addressed until management of these systems has improved. Even if the institutional capacity were in place, however, there are no guidelines for leakage control in the small and medium-sized water systems of the developing world. It is also true that some leakage reduction can be effected while institutional capacity building is still taking place. We have chosen, therefore, to focus on the technical aspects of leakage control, assuming a minimum of institutional capacity already in place.

In answer to the question of "where to begin" and what to do about leak detection in small water systems in developing countries (under conditions described in section 6.1), therefore, we have suggested the following:

--There must be some sort of centralized water authority (responsible for other aspects of management as well as leakage control). A regional leak detection crew should be trained, and be responsible for detection in all small water systems in the area.

-- Sonic detection (sounding) is the only appropriate method of leak detection for these systems, and can be carried out at pressures somewhat lower than those cited in the literature.

-- An assessment of the overall leakage level is not necessary here, despite the fact that it is regularly carried out in industrialized countries. It is extremely difficult to do under the conditions assumed here, and is not needed because we are not trying to choose an optimum level of leakage. The only relevant figure is that leakage which is actually discovered during leak detection.

-- Mapping of the distribution system is important in the long run, and for reasons other than just leakage control, but some leak detection can be effected before the mapping is completed. Completion of an inventory of the system will take a long time, and some of the data can be gathered in conjunction with the leakage detection and repair.

-- Areas with high levels of surface leakage and a high value of water should be the first to be investigated by active sounding. It is important to establish priorities and carry out leak detection where the returns are expected to be greatest, because funds are so scarce. It is also important to calculate the actual benefit/cost ratios after the program has been carried out, to ensure that the leak detection efforts are indeed economically justified.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

This phase of research has consisted of: an extensive review of the literature on unaccounted-for water; the decision to focus on the problem of underground leakage; an attempt to develop an optimal approach to leakage control in developing countries and the realization that this was not possible; an examination of predictive models and the realization that this was not applicable to developing countries either. Our final attempt was to outline a reasonable (rather than optimal) approach to take in determining priorities for leak detection in small water systems in developing countries, where it is expected that underground leakage is a large problem, though not always recognized, and where little has been done as yet toward leakage control because the problem seemed too intractable.

The next step, then, would be field research in some country where A.I.D. is working in the water sector, and where there is some regional or national agency concerned with water resources. The researcher would work with this agency in field testing the procedure described in section 6.6 of this report. It is anticipated that under field conditions, substantial modifications to the procedure would be necessary; it is hoped that the product of this second phase of research would be a set of guidelines which could be used by managers of small water utilities in developing countries in controlling leakage.

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TABLES AND FIGURES

TABLE 1

Unaccounted-for Water in Selected Cities Around the World

CITY	% of Total Production UFW	LEAKAGE	METER ERROR	ILLEGAL USE	DEFINITION OF UNACCOUNTED-FOR WATER
Cambridge, Mass. (Babcock, 1984)	20	13	2 or 2.5		Accounted: metered residential, industrial, commercial, institutional, construction; estimated municipal and fire supply Unaccounted*: reservoir leakage, meter under-registration, estimated unavoidable leakage, leakage found in survey, unknown.
Gary, In. 1957 (Pilzer, 1981)	20				(Unaccounted not defined)
Boston 1978 (Sullivan, 1981)	45	17.5	21.7		Unaccounted: meter under-registration, leaks & breaks, blowoffs & flushings, fireflow, unmetered public use
Perth (Hanke, 1981)	29	15			Accounted: metered residential, metered non-residential Unaccounted: unmetered use, leakage
Hong Kong (World Water, 1983a)	30		>17	~ 1.5	Unaccounted: meter error, illegal connections, leakage in distribution, leakage in service reservoirs, leakage in consumers' plumbing, fire flow, water used in operations
Manila 1970-78 (World Water, 1983b)	50				(Unaccounted not defined)
Manila pilot project, 1983 (World Water, 1983b)	70				70% defined as Non-Revenue Water
Bangkok (CDM-MEC 1983)	45	32 - 40	2 - 6	2 - 5	Accounted: billed Unaccounted: metering losses, illegal use, public use, leakage
Semerah, Malaysia (WHO/WB, 1982)	50				(Unaccounted not defined, includes at least leakage, illegal connections)
São Paulo 1978 (Riomey,1982)	38				(Unaccounted not defined, includes at least meter under-registration)
Libreville 1976 (Courteau, 1979)	43				Accounted: water sold
Addis Ababa (Bridger, 1983)	22	15			Unaccounted: leakage from pipes, service reservoirs, pumping stations; unmetered use of water (none); meter error, under-billing, illegal connections

* "unaccounted-for" used in text to mean "unknown"

TABLE 2

Categorization of Leaks in Water Distribution Systems

		Mamaroneck, N.Y. (1st survey) (Moyer et al, 1982)	Mamaroneck, N.Y. (3 surveys) (Moyer et al, 1982) *	Long Island, N.Y. (Marchon, 1985)	Schenectady, N.Y. - Low Zone (Lilley, 1984)	Schenectady, N.Y. - Woodlawn (Lilley, 1984)	Schenectady N.Y. - Bellevue (Lilley, 1984)	Daytona Beach, FL (Curtiss, 1983)	Boston, MA (Sullivan, 1981)	46 surveys / Heath Co. (Cole, 1983)	FEDERAL REPUBLIC OF GERMANY (Laske et al, 1981)	Barranquilla, COLOMBIA (Heath, 1985)
KM OF MAIN SURVEYED:		302	302	32	24.1	22.4	11.6	53	?	?	400	302.7
% OF TOTAL NUMBER OF LEAKS	hydrants	54.8	62.4	58.3	}71.4	}81.0	}40.0	15.6	34.1	40	}37	7.3
	valves			}25.0				6.7	0.8	20		1.2
	mains	21.5	15.2		0	0	20.0	4.4	}7.2	15	17	4.5
	joints											
	service	23.7	22.4	16.7	28.6	19.0	40.0	73.3	58.0	25	46	87.0
	(customer)	(9.0)	(7.9)					(64.4)				
	(utility)	(14.7)	(14.5)					(8.9)				
% OF LEAKAGE VOLUME	hydrants	24.2	20.0	16	}20.9	}49.7	}10.5	14.2	3.6		}11	8.5
	valves			}80				2.8	0.1			0.5
	mains	50.6	48.1		0	0	37.3	16.4	}23.6		30	16.0
	joints											
	service	25.2	31.9	4	79.1	50.3	52.2	66.6	72.7		59	75.0
	(customer)	(8.5)	(10.4)					(46.3)				
	(utility)	(16.7)	(21.5)					(20.3)				
AVERAGE LEAKAGE RATE (m^3/DAY/LEAK)	hydrants	34.9	19.1	46.7	}24.7	}25.3	}19.1	14.1	8.6			13.6
	valves			}559				6.3	19.7			5.3
	mains	185.8	188.6				136	56.8	}269			41.9
	joints											
	service	84.3	84.5	40.9	234	109	95.4	13.9	103			10.0
	(customer)	(74.1)	(78.5)					(11.0)				
	(utility)	(89.9)	(87.7)					(35.0)				
	overall	76.8	57.8	174	84.4	41.2	72.9	15.4	82.1			11.7
m^3/DAY/KM		46.3		64.8	147	38.6	31.4	12.8			12	9.5
LEAKS/KM		.60		.37	1.7	.94	.43	.83				.82

* These figures are an average of three surveys done at 2-year intervals.

TABLE 3

Levels of Net Night Flows in Large Urban Areas in the United Kingdom

Leakage control method	Areas where leakage is typically Low (l/prop/hr)	Medium (l/prop/hr)	High (l/prop/hr)
Passive leakage control	15	18	25
Regular sounding	8	10	14
District metering	6.5	8	11
Waste metering	5	6	8
Combined district and waste metering	5	6	8

From NWC, 1980, p. 36

TABLE 4

Costs of Components of Leakage Control Methods
(at mid-1979 Levels) in the U.K.

Operation	*Mean cost* £	*Typical range of costs* £
Install a waste meter and set up district	1,650	1,000–2,000
Record a night line (day/night work)	36	18– 54
Record a night line (night work only)	52	26– 78
Perform a step test	85	60– 110
Sound 1,000 houses	150	100– 300
Read 100 district meters	80	60– 100
Repair backlog of leaks found when introducing active leakage control (per 1,000 properties)	300	200– 500
Locate reported leaks when operating passive leakage control (per 1,000 properties)	60	0– 300
Install PRV and set up pressure zone	1,750	500–3,000
Annual PRV maintenance	25	10– 50
Sound a trunk main (per km)	6	2– 12
Install a tapping and chamber	150	100– 500
Perform leakage measurement using a heat pulse meter or bypass meter	35	15– 70
Locate leakage by SF_6 gas tracing (per km) in soft ground	60	
Perform reservoir drop test	35	15– 70
Locate leakage using leak noise correlator (per 200m)	15	10– 20

From NWC, 1980, p. 37

TABLE 5

Synthesized Cost to Repair Ductile Iron Main Breaks: 1980 Dollars

Pipe Diameter

in.	4	6	8	10	12	14	16	18	20	24
mm.	100	150	200	250	300	350	400	450	500	600
Crew	$256	$290	$315	$336	$356	$372	$383	$397	$412	$430
Equipment	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45
Sleeve	$ 53	$ 67	$ 77	$ 93	$112	$239	$268	$280	$290	$507
Repaving	$120	$120	$120	$120	$144	$144	$144	$144	$192	$192
Overhead	$ 95	$104	$111	$119	$133	$160	$168	$173	$188	$235
Total	$572	$626	$668	$713	$799	$960	$1008	$1039	$1127	$1409

From Walski & Pelliccia, 1982, p. 142

TABLE 6

Average Costs, Benefits, and Net Benefits of Leak Detection and Repair for Three Surveys, Dollars/Leak

Type of Leak	Cost	Benefit	Net Benefit
Hydrant	$336	$275	-$ 61
Service-Customer	$274	$1081	$ 807
Service-WJWW	$836	$1202	$ 366
Main	$837	$2654	$1817
No Leak Found	$645	$ 0	-$645
Other*	$267	$ 0	-$267
All Types	$480	$806	$ 326

* Leaks found on the distribution systems of other utilities.

From Moyer et al
1982, p. 365

TABLE 7

Data for Establishing Leak Detection Priorities

	ZONES A	B	C	D	E	
LEAKAGE:						
m^3/day/km *	40	30	25	18	12	(V_{P_i})
leaks/km *	13	8	10	8	5	(N_{P_i})
COST OF WATER:						
\$/m^3	.15	.18	.23	.15	.20	(W_i)

* Repairs made under passive control, numbers and rates measured over the same time period.

TABLE 8

Calculation of Priorities for Leak Detection

	ZONES A	B	C	D	E
$P_i' = \frac{V_{P_i} W_i}{N_{P_i}}$	.462	.675	.575	.338	.480

Order of priorities is: B, C, E, A, D.

FIGURE 1

Flow of Water in a Water Supply and Distribution System

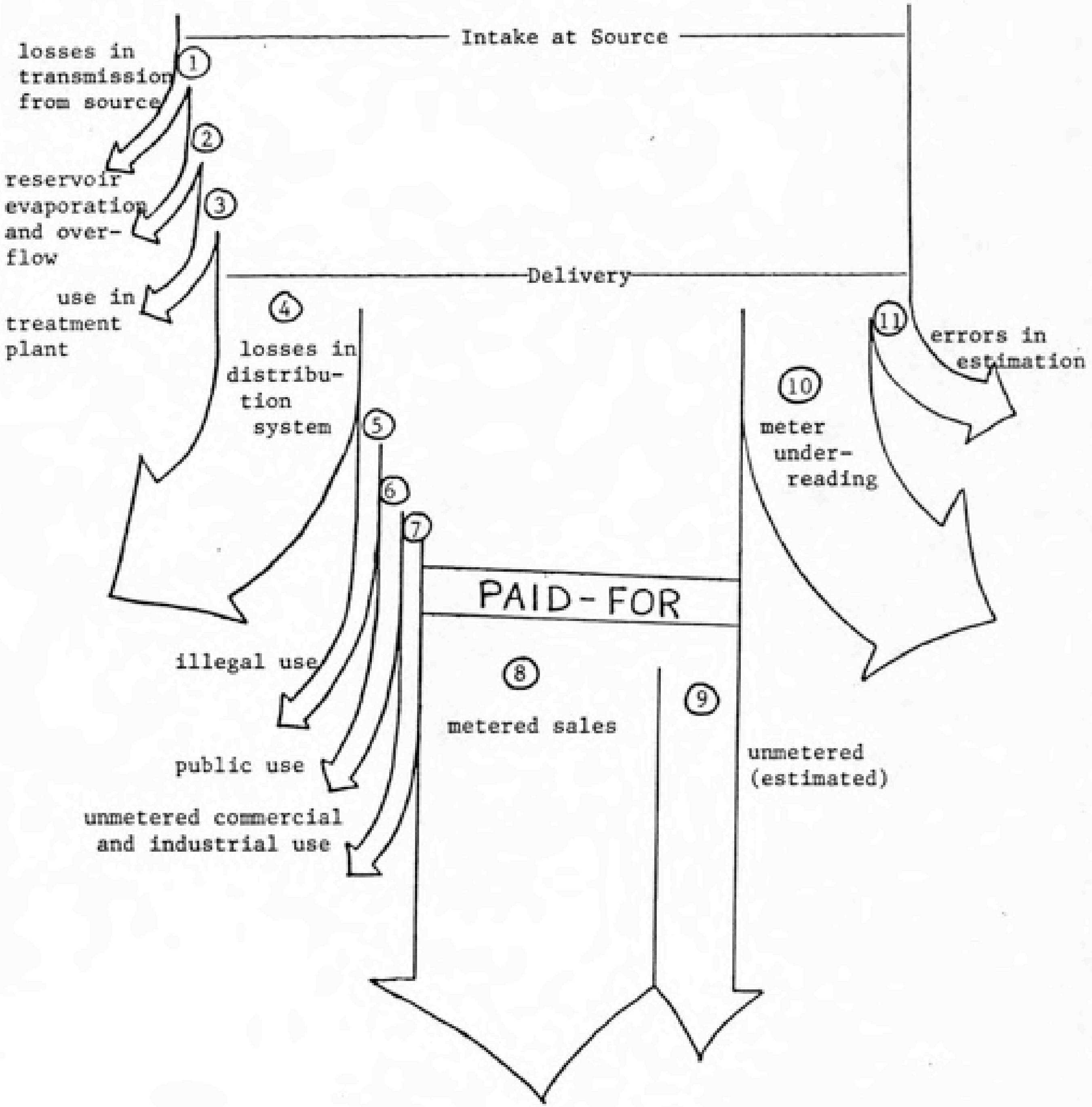


FIGURE 2

Major Factors Affecting Leakage in Water Distribution Systems

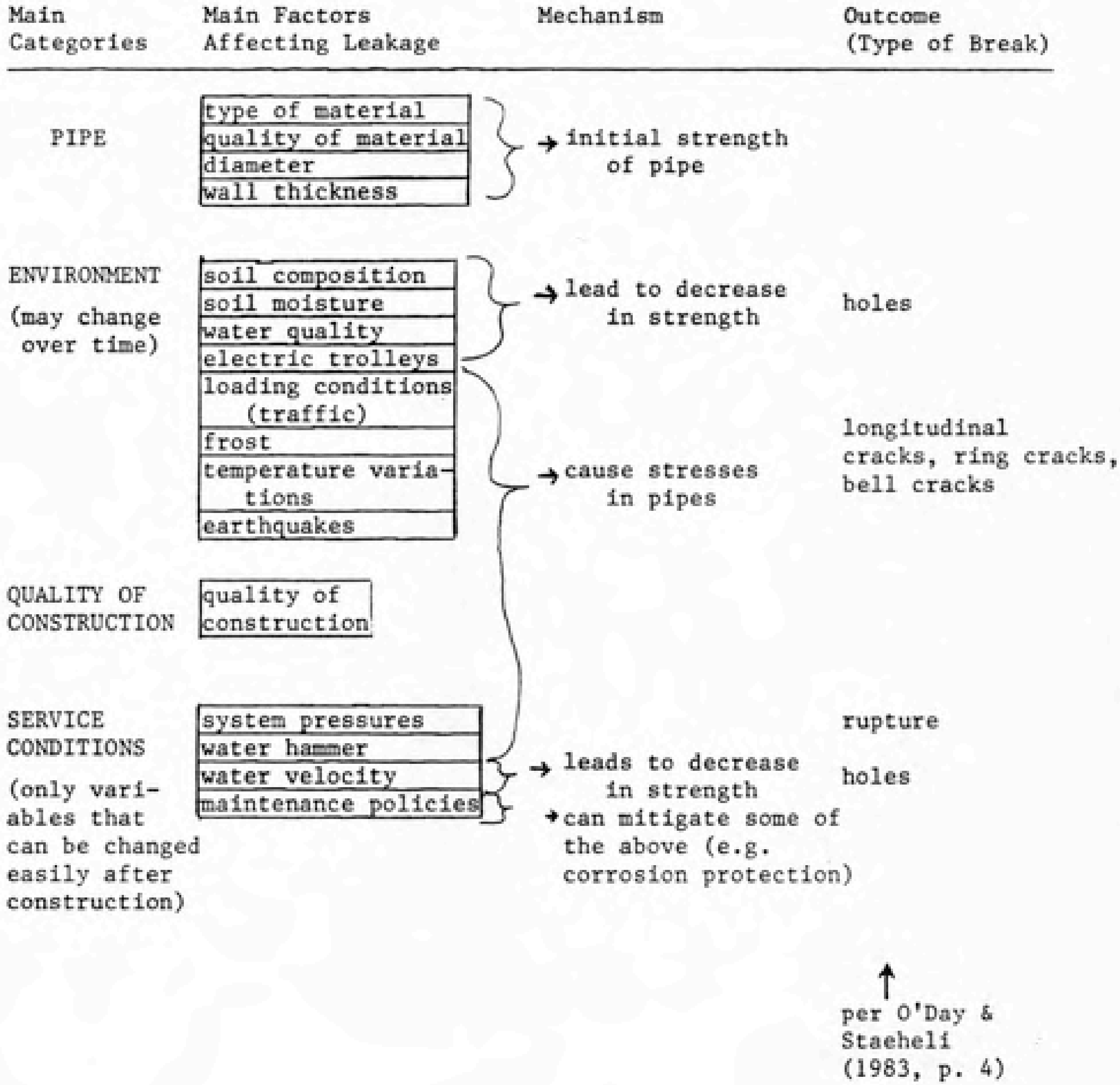
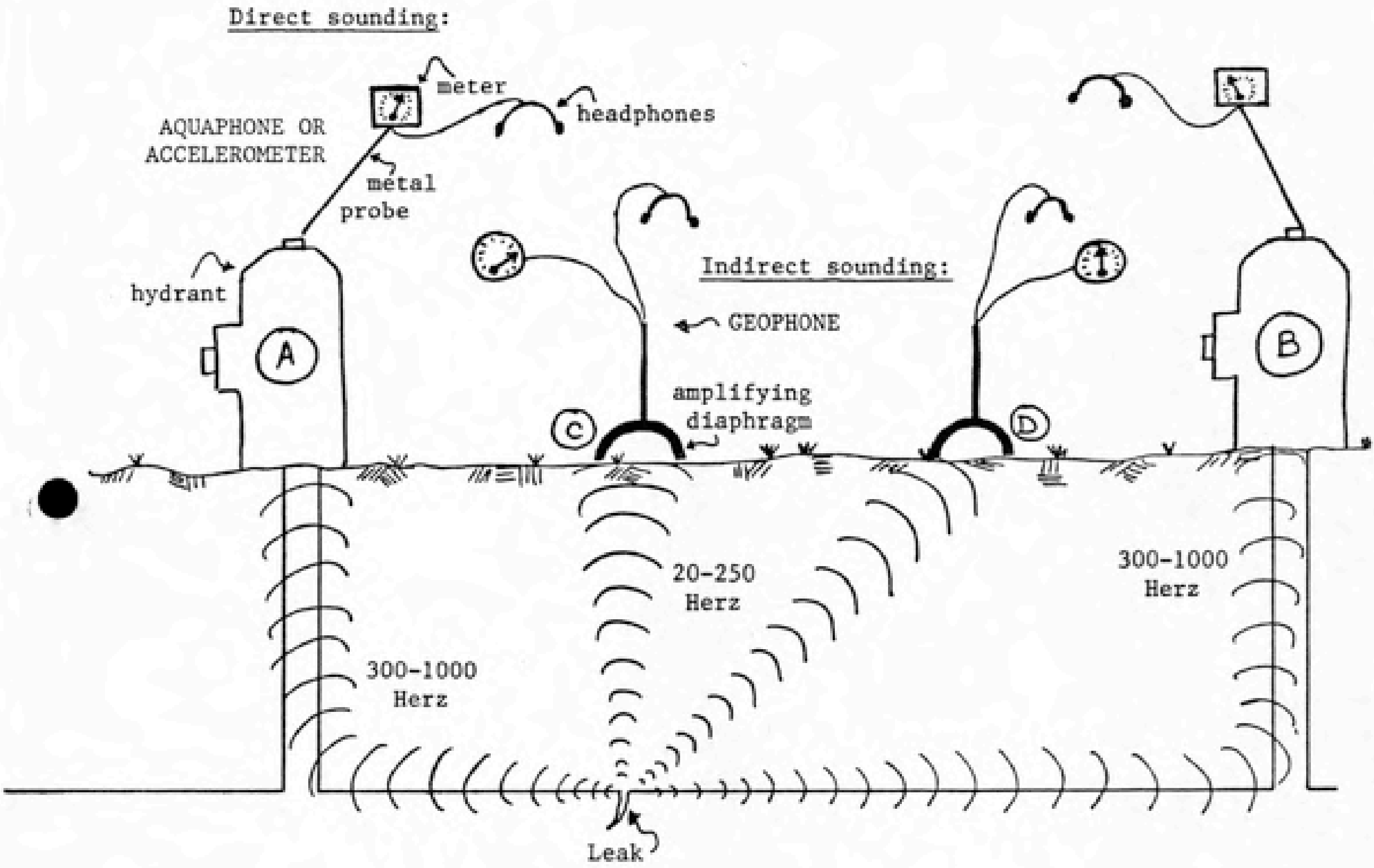


FIGURE 3

Common Methods of Direct and Indirect Sounding for Leaks



F I G U R E 4

Less Common Methods of Sounding

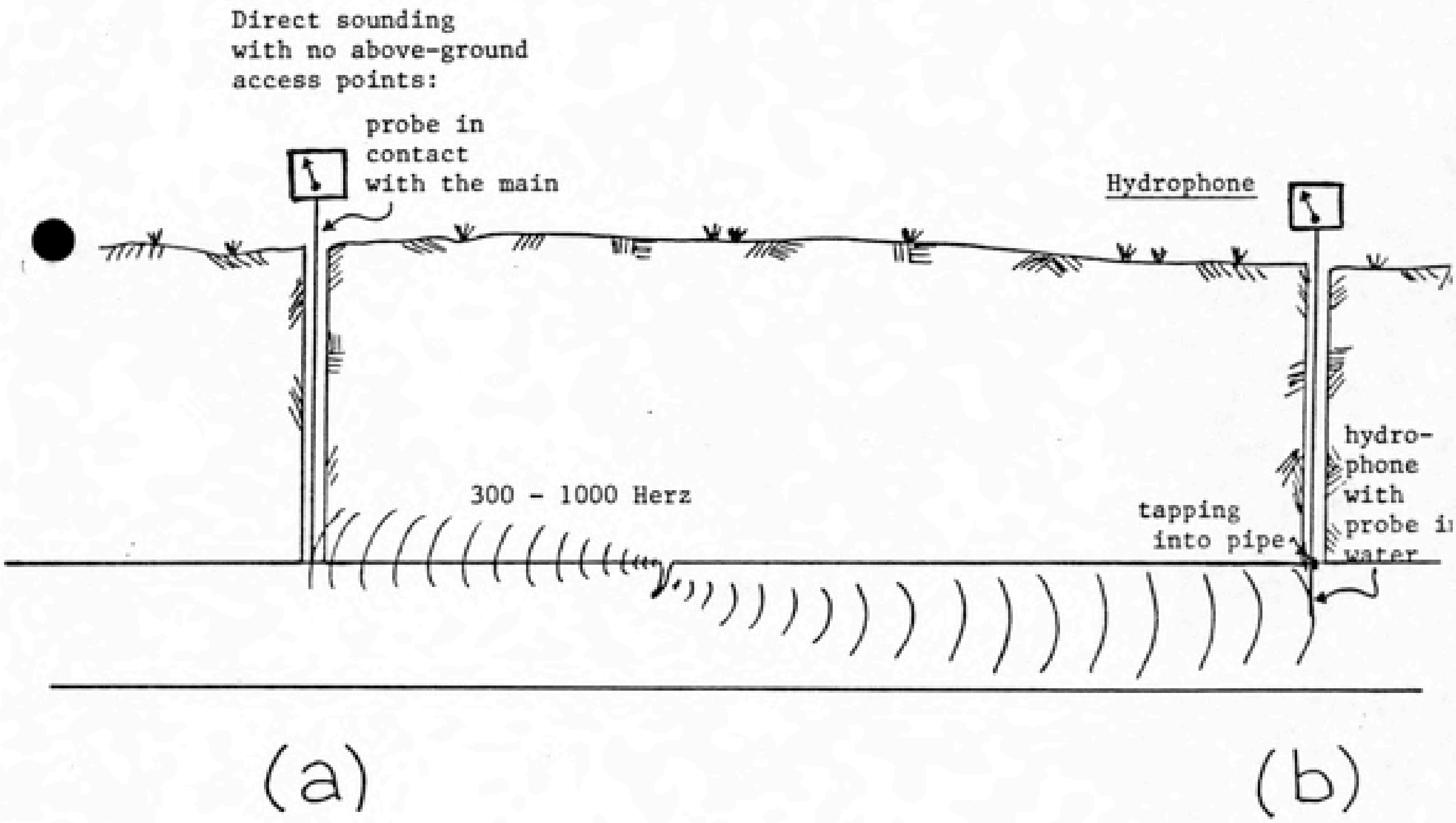
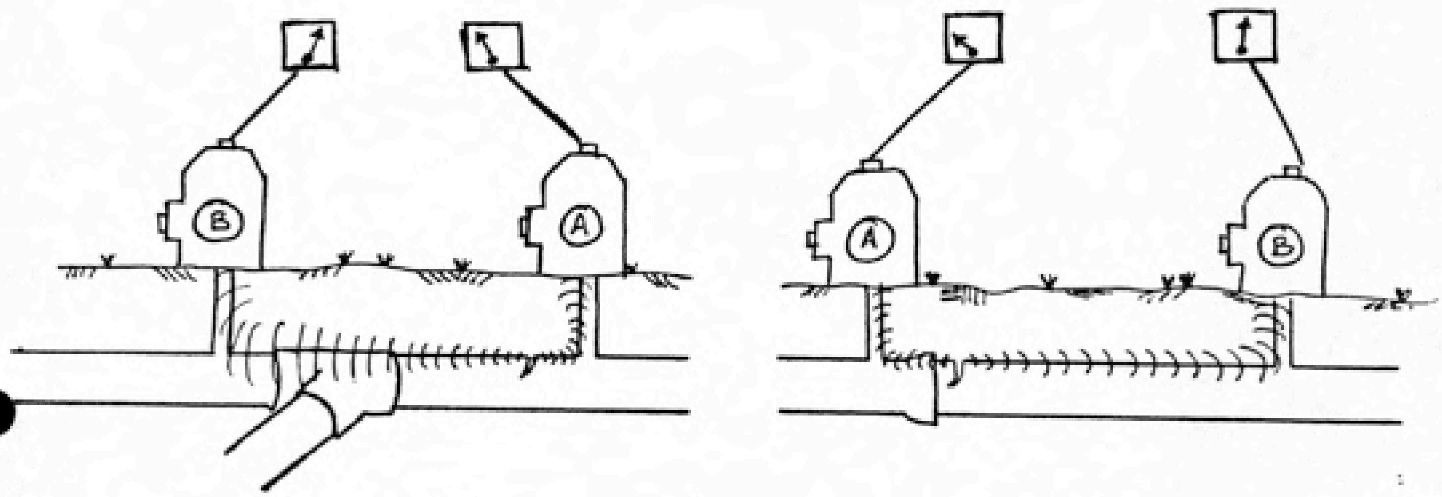


FIGURE 5

Problems in Pinpointing a Leak (Direct Sounding)

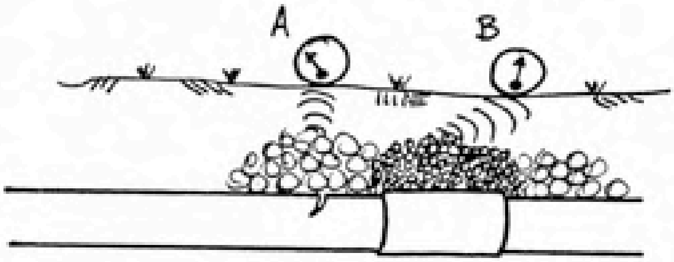


(a) Amplification of sound at a tee

(b) Deadening of sound at a joint

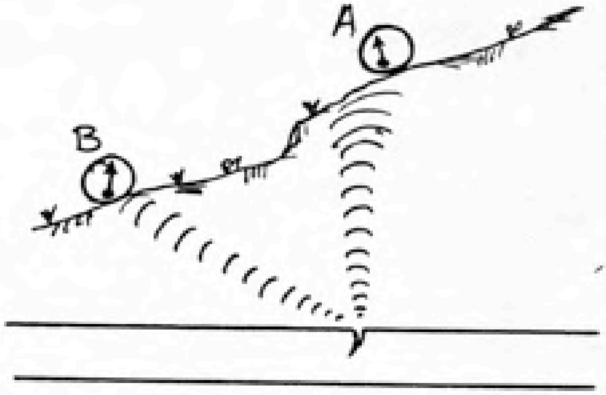
FIGURE 6

Problems in Pinpointing a Leak (Indirect Sounding)



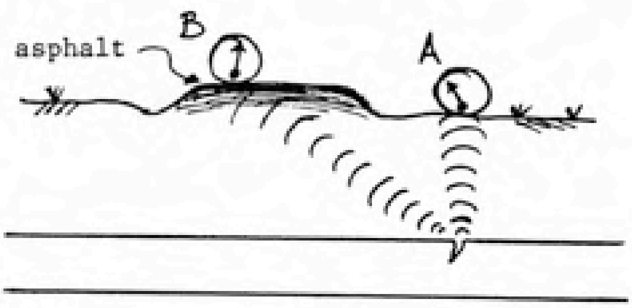
(a)

Backfill of varying acoustic properties (better transmission of sound to point B due to different backfill)



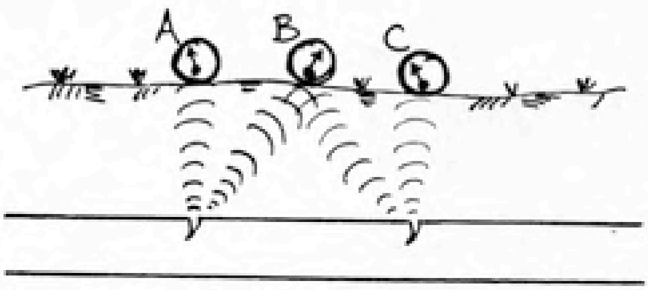
(b)

Effect of varying depth of ground cover (shorter travel path to point B)



(c)

Effect of varying types of surface



(d)

Effect of multiple leaks

FIGURE 7

Gas Tracer Method of Leak Detection

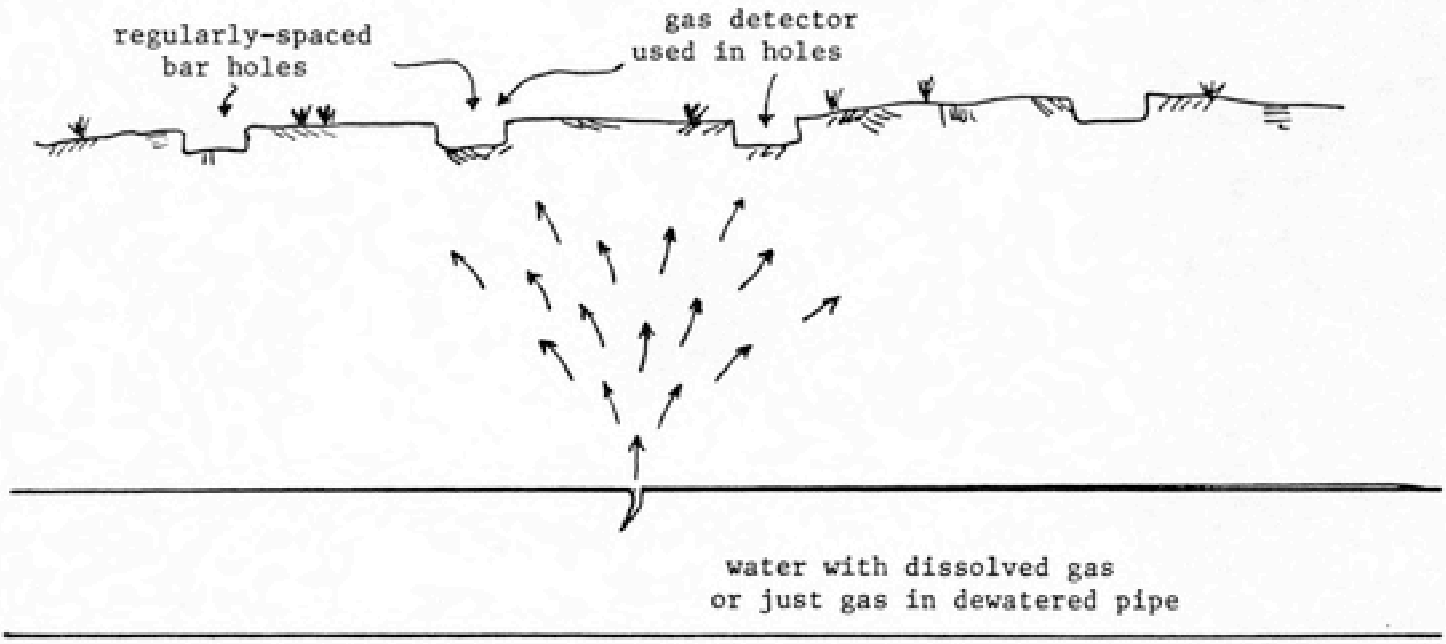
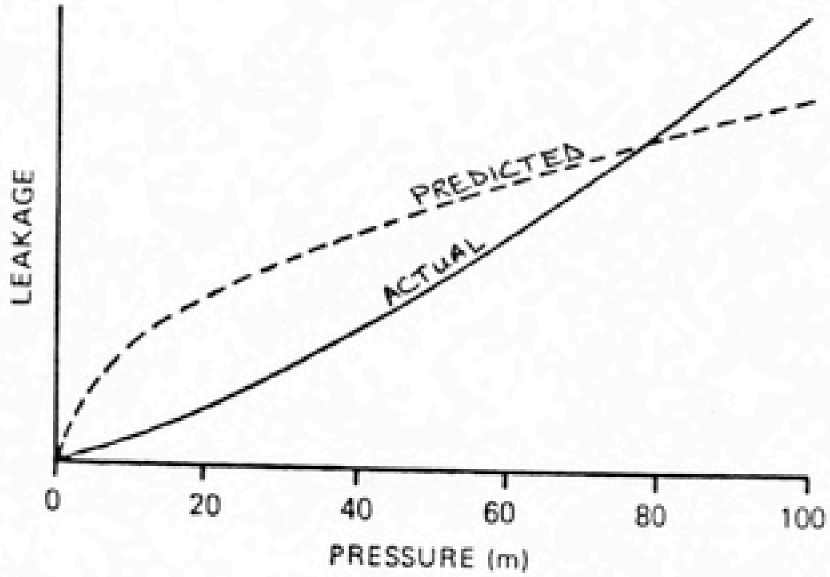


FIGURE 8

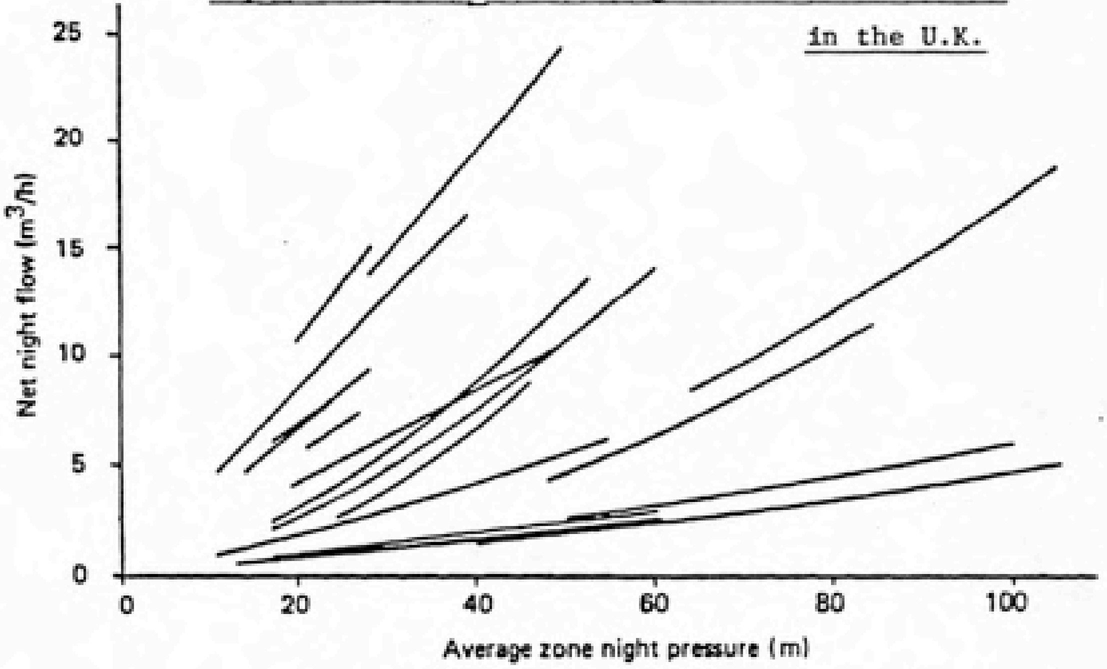
Observed vs. Predicted Relationship Between System Pressure and Leakage



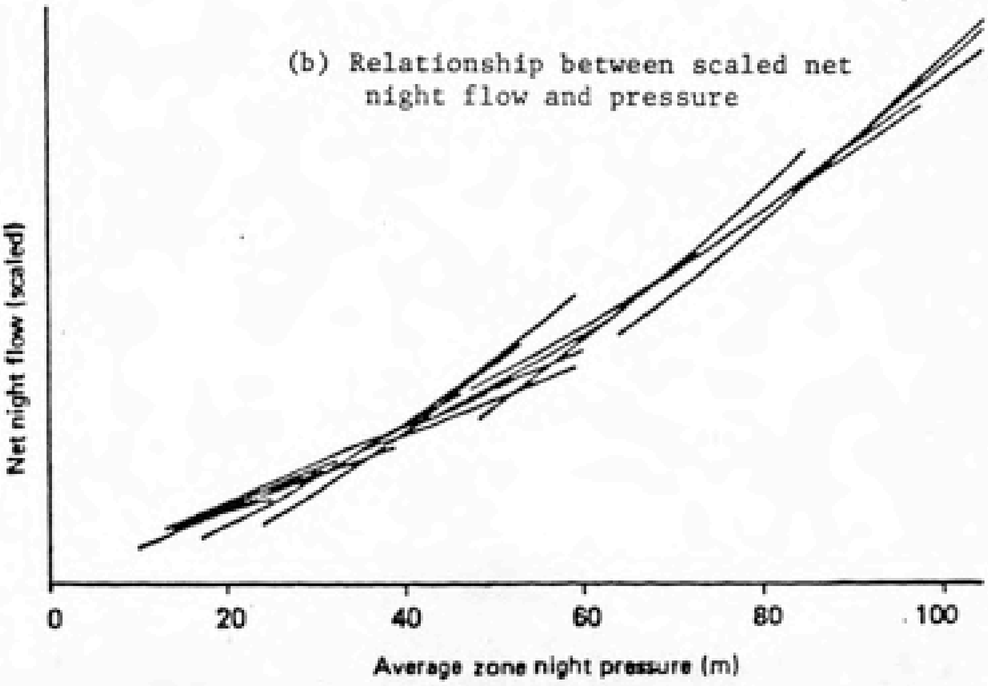
From NWC, 1980, p. 36

FIGURE 9

Experimental Data on Net Night Flows vs. Pressure in the U.K.



(a) Relationship between net night flow and pressure

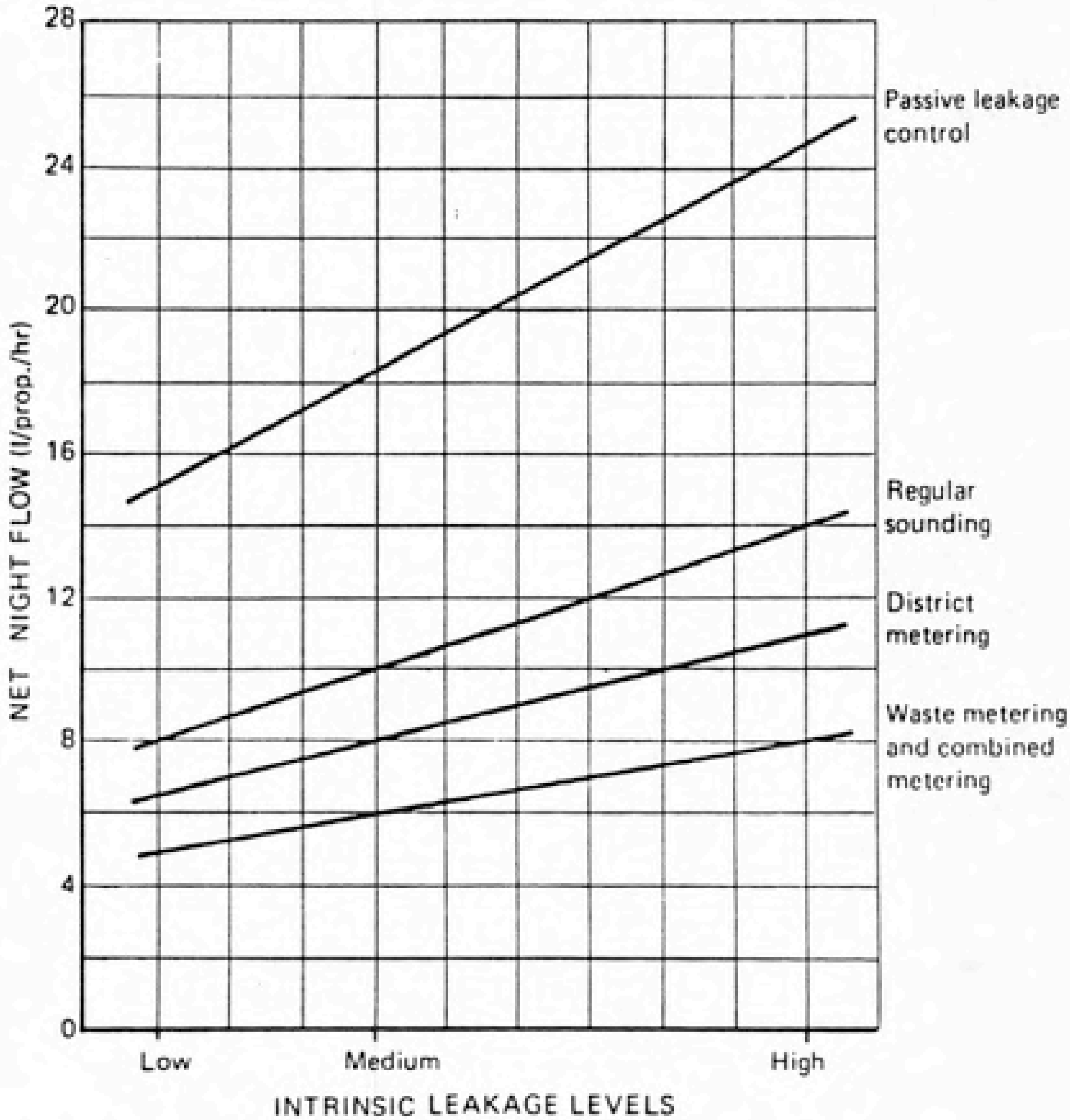


(b) Relationship between scaled net night flow and pressure

From Goodwin, 1980, p. 28

FIGURE 10

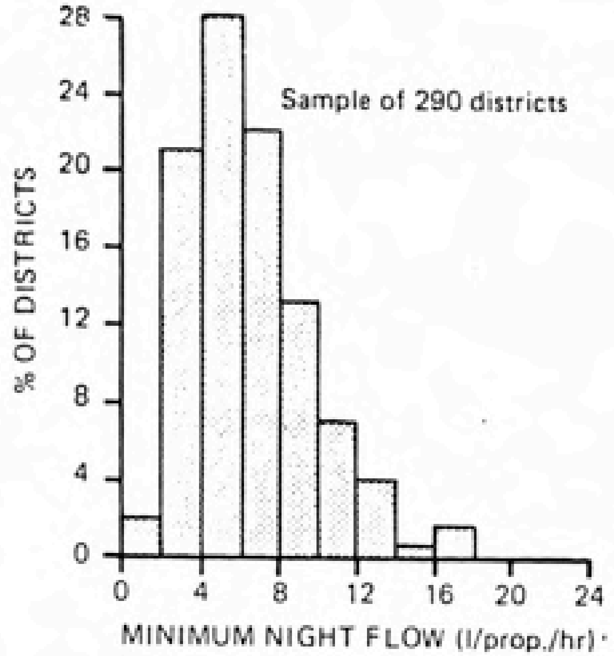
Graph for Prediction of Net Night Flows in the U.K.



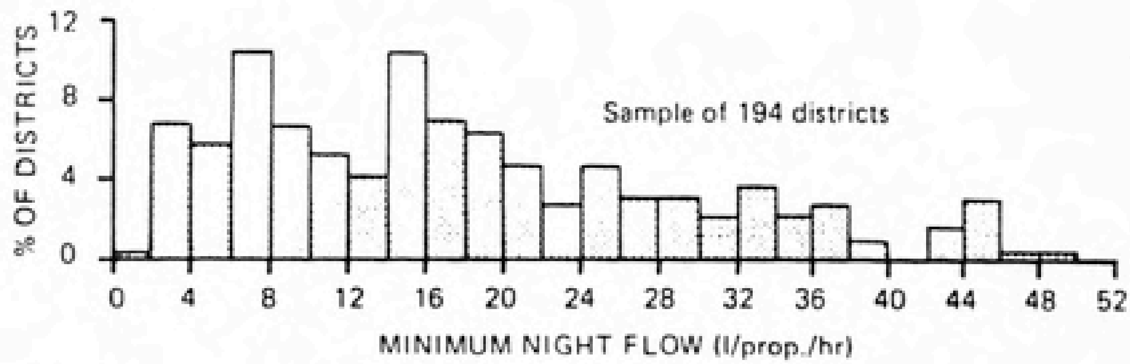
From NWC, 1980, p. 45

FIGURE 11

Net Night Flows under Different Control Methods in the U.K.



(a) Histogram of night flows in districts with effective waste metering



(b) Histogram of night flows in districts with passive leakage control

From NWC, 1980, pp. 34-35

EXHIBIT 1

PRIORITIES (for leak detection aid to water systems in North Carolina)

SYSTEM: ____________________

			Priority Points
I.	Unaccounted For Loss Per Mile Pipe/Day	Under 1,000	0
	• Unaccounted for ________ gallons	1,000 - 5,000	2
	• Miles of distribution lines _____	5,000 -10,000	5
	• Unaccounted for ÷ miles _______	Over 10,000	10
II.	Urgency		
	• Whole system out of water		15
	• Portion of system out of water		12
	• Reduced pressure		6
	• No urgency, but considered a problem (known leaks, not pinpointed)		3
	• Uncertain if problem exists		0
III.	Size of Community		
	• Under 500 connections		10
	• 500 to 2,000 connections		8
	• 2,000 to 5,000 connections		4
	• 5,000 to 10,000 connections		1
	• Over 10,000 connections		0
IV.	Prior Assistance		
	• Never assisted		10
	• Assisted once, or has had consultant studies within the last year		2
	• Assisted more than once		0
V.	Current Assistance		
	• Has totaled water pumped vs. water sold within the last 6 months, no equipment, eager		10
	• Has no equipment, personnel available and eager		5
	• No staff available to assist, or have not used equipment for two weeks		0
VI.	Time Delay - 2 Pt./month		
	Date of request ______________		____
		TOTAL	____