# The Design and Application of
# SLOW SAND FILTRATION IN DEVELOPING COUNTRIES

## Report 1

# Rural Water Supply and the Use of Slow Sand Filters in PERU

by

Patrick A. Mullen

Department of Civil Engineering
University of Notre Dame
Notre Dame, Indiana 46556
U. S. A.

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# PREFACE

In March 1988 I spent two weeks in Peru. The purpose of my trip was to collect information about the design and application of slow sand filtration in the small, rural communities. My hosts were Eng. Henry Salas of the Pan-American Center for Sanitary Engineering and Environmental Sciences (CEPIS), an affiliate of the Pan-American Health Organization and Eng. Ricardo Rojas of DelAgua, Ltd. a private British development agency linked to the University of Surrey in Guildford, England.

During the first week -- which I spent in Lima, the capital -- I had the opportunity to discuss rural water supply and Peru's experience with slow sand filtration with Eng. Rojas; review literature on slow sand filtration in CEPIS's library; and meet with a design engineer in the Rural Sanitation Division (DISABAR) of the Ministry of Health, the government agency responsible for rural water supply. At the end of the first week I also toured the water supply system in San Vincente de Azpitia, a small village about 100 kilometers south of Lima.

At the beginning of the second week I travelled into the Andes mountains to the city of Huancayo in the department of Junín. During that week Eng. German Martinez of DISABAR's regional office accompanied me on a tour of water treatment plants in four rural villages in the vicinity of Huancayo. The four treatment plants were in various stages of operation, construction or abandonment which proved useful for puposes of comparison.

The following report is a presentation of what I learned about rural water supply in Peru during my two weeks there. It includes information I collected from my discussions with engineers and my review of literature, documents and design drafts. The main focus of the report is on Peru's experience with slow sand filtration, but the Introduction and the chapter entitled "Site Visits" also present a more general discussion of rural water supply and an account of my visits to the five water treatment plants.

## ACKNOWLEDGMENTS

I would like to thank the Zahm Research Travel Fund of the University of Notre Dame for the travel grant which helped finance my trip to Peru.

I would also like to take the opportunity this section offers to extend my appreciation to the following people:

Henry Salas of CEPIS for helping to arrange for my trip to Peru and my stay in Lima;

Ricardo Rojas of DelAqua for kindly taking the time to discuss water supply and sanitation in Peru, for taking me to meet engineers at DISABAR, and for driving down to Azpitia and giving me a tour of that community's water supply system;

Jamie Bartram of DelAqua for allowing me to hitch a ride up to Huancayo in the Land Rover and for the companionship during my stay in that city (for which I should also thank Andy, Warren, and Enrique);

German Martinez of DISABAR-Huancayo for all the time he spent giving me the grand tour of the rural communities around Huancayo, including the four water treatment plants, the local artisanry, and the world's best trout;

And finally, the Gonzalez family: Señor and Señora Gonzalez for providing a home-away-from-home in Lima; Sissy for taking me out with her and her friends; and Oscar for putting me in contact with his wonderful family.

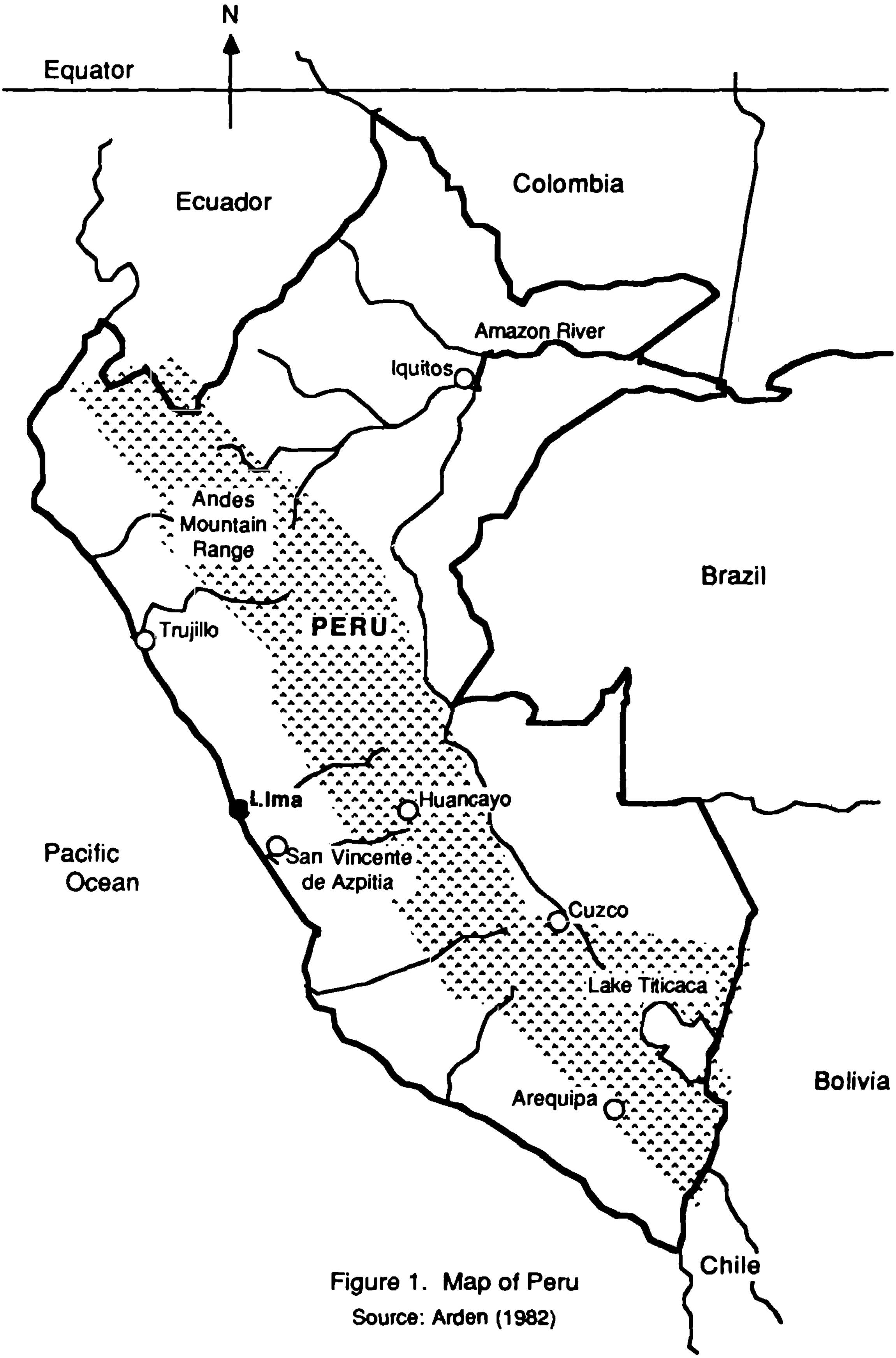


Figure 1. Map of Peru
Source: Arden (1982)

# INTRODUCTION

Peru is a South American country bounded to the North by Ecuador and Colombia, to the South by Bolivia and Chile, to the East by Brazil and to the West by the Pacific Ocean (see Figure 1). Peru consists of three distinct geographic regions (Figure 2) delineated by the towering Andes Mountains which run the length of the country: the extremely-arid Pacific coast region, known as the *costa*, which includes the capital, Lima; the Andes highlands or *sierra*; and the *selva*, the Amazon rain forest region to the east of the Andes.

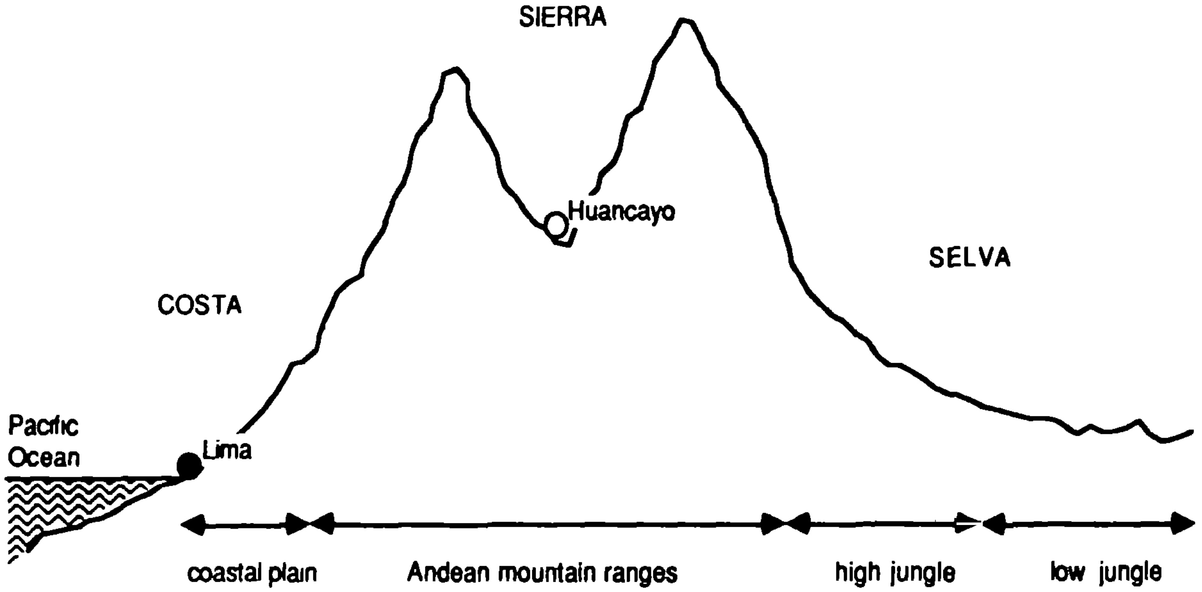


FIGURE 2. Cross-Section of Peru
Source: DelAqua (1986), p.12

Peru has a total population of about 18.6 million people (World Bank, 1987) of which approximately 65% live in urban areas and 35% live in rural areas (see Table 2). Poverty, unemployment and lack of basic government services in rural areas have engendered massive migration from the countryside to Peruvian cities, especially Lima. Urbanization, in turn, has generated increased unemployment, crime, and squalor in the cities. Improving living conditions in rural areas by increasing government services (such as water supply,health care and education) is one way to render urban migration less attractive. Unfortunately, Peru's poor economic conditions (e.g., 98.6% inflation) and large external debt ($13.7 Billion) -- as well as the government's bias toward urban development -- make massive rural development efforts unlikely (World Bank, 1987).

While by world standards, Peru is considered a middle to lower-middle income economy, its per capita GNP of $1010 makes it one of the poorest countries in South America (World Bank, 1987). Life expectancy for Peruvians is 59 years, infant mortality is 94 per 1000 live births and the child death rate (for ages 1-4) is 11 per 1000 (World Bank, 1987). Among South American countries only Bolivia has consistently worse basic indicators.

TABLE 1
Per Capita GNP and Basic Quality of Life
Indicators for South American Countries

| Country | Per Capita GNP (1985 Dollars) | Life Expectancy (male/years) | Infant Mortality (per 1000) | Child Death Rate (per 1000) |
|---|---|---|---|---|
| Bolivia | $470 | 51 | 117 | 20 |
| Paraguay | $860 | 64 | 43 | 2 |
| PERU | $1,010 | 57 | 94 | 11 |
| Ecuador | $1,160 | 64 | 67 | 5 |
| Colombia | $1,320 | 63 | 48 | 3 |
| Chile | $1,430 | 67 | 22 | 1 |
| Brazil | $1,640 | 62 | 67 | 5 |
| Uruguay | $1,650 | 70 | 29 | 1 |
| Argentina | $2,130 | 67 | 34 | 1 |
| Venezuela | $3,080 | 66 | 37 | 2 |

Source: World Bank (1987)

## Rural Water Supply in Peru

The Rural Sanitation Division (DISABAR) of the Ministry of Health, the government agency responsible for rural water supply in Peru, has, for simplicity, defined rural communities as those with populations of 2000 or less. Of these, DISABAR only deals with those of more than 100 inhabitants; officials deem smaller communities too numerous and too dispersed to make the provision of water supply systems for all financially feasible (Bartram et al., 1987). In any case, the bulk of Peru's rural population lies in villages of 100 to 1000 (Table 2).

Despite efforts by DISABAR and various international aid agencies, the rural water supply situation in Peru remains dire. In 1983 the U.S. General Accounting Office reported that 78% of the rural population in Peru had no potable water (USGAO, 1983). In 1986 the Peruvian Ministry of Health estimated that in 1987 only 29% of rural people would be served by drinking water (Bartram et al., 1987). The unavailability of safe drinking water to the bulk of Peru's rural population is a major reason for the high infant mortality and child death rates. Enteric diseases related to contaminated drinking water supplies remain widespread in rural areas.

## TABLE 2
## Peru: Total Population by Urban and Rural Area and by Size of Population Center

| Size of Population Center by Number of Inhabitants | Number of Populated Centers | Population<br>Total | <br>Urban | <br>Rural |
|---|---|---|---|---|
| Total | 63,666 | 17,055,210 | 11,091,923 | 5,913,287 |
| <50 | 34,239 | 570,653 | 371 | 570,282 |
| 50-99 | 9,850 | 684,658 | 3,468 | 681,190 |
| 100-199 | 9,063 | 1,289,272 | 21,874 | 1,267,398 |
| 200-499 | 7,816 | 2,399,460 | 198,147 | 2,201,313 |
| 500-999 | 1,915 | 1,294,824 | 414,570 | 880,254 |
| 1,000-1,999 | 581 | 788,717 | 541,888 | 246,829 |
| 5,000-9,999 | 246 | 739,700 | 681,789 | 57,911 |
| 10,000-19,999 | 41 | 642,134 | 634,024 | 8,110 |
| 20,000-49,999 | 44 | 1,431,874 | 1,431,874 | - |
| 50,000-99,999 | 26 | 1,868,099 | 1,868,099 | - |
| 100,000-199,999 | 16 | 2,366,105 | 2,366,105 | - |
| 200,000-499,999 | 8 | 2,371,676 | 2,371,676 | - |

Source: Bartram et al. (1987), p.12 -- National Census of Population (1981)

Like many other developing countries, Peru's ability to provide drinking water to all communities is hampered by the scarcity of funds and trained personnel. Another reason for such water supply deficiencies is that while a good proportion of Peruvian communities have water systems, the provision of water to households within these communities is far from complete. For example, 54.4% of the communities in the departments of Junín, Cerro de Pasco, and Huancavelica (the Health Ministry's "Pilot Region") are covered by water supply systems, but the average coverage within those communities is only 56% (Bartram et al.,1987).

Just as serious as the problem of insufficient coverage is that of poor performance (and failure) of existing water supply systems. In this case, the chief culprits are inadequate operation and maintenance and faulty design, both of which will be discussed in more detail in the next chapter ("Slow Sand Filtration"). Suffice it to say, for present purposes, that the poor performance of existing water supply systems has forced DISABAR to carry out a number of "rehabilitation" projects designed to restore failing systems to effective operation.

### Types of Water Supply Systems

DISABAR divides water supply systems in Peru into four categories: 1) gravity without treatment, 2) gravity with treatment, 3) pumped without treatment, and 4) pumped with treatment. Examples of each category are shown in Table 3.

Because of the steep terrain in much of Peru, the use of gravity to move water from its source to its distribution points is quite common. Pumps -- typically the

TABLE 3
DISABAR's Classification of Water Supply Systems

| | Treatment | |
|---|---|---|
| | Yes | No |
| Gravity | gravity-flow surface water treatment plant | spring water |
| Pumped | conventional surface water treatment plant | well water (ground-water) |

component of a water supply facility most prone to failure -- are rarely required in Peru's rural water supply systems, something which has dramatically reduced the cost and complexity of these systems. The use of gravity-powered flow is especially common in villages of the Andean highlands (*sierra*) and the many communities which lie at the foot of the Andes in the Pacific coast region (*costa*). Pumps are needed principally in the tropical rain forests (*selva*) of eastern Peru, where the mountains end and the Amazon river basin begins.

Of the two types of gravity-flow water system, by far the most common in the rural areas of Peru is the protected spring (Table 4), but there are also a considerable number of communities without convenient access to springs that are forced to use surface water sources instead. Since surface water is typically very turbid and heavily-contaminated by human waste, it must be treated to remove suspended solids and pathogenic organisms. The treatment of surface water supplies in gravity-flow systems -- that is, gravity with treatment -- is the primary focus of this paper.

TABLE 4
Population Served and Percentage Coverage
by Supply Type in the Department of Junín

| System Type | Total Number of Systems | Total Served Population | Percentage of Total Rural Population with Water Supply Served by System Type |
|---|---|---|---|
| gravity w/o treatmt | 273 | 191,898 | 84% |
| gravity w/treatmt | 25 | 25,924 | 11% |
| pumped w/o treatmt | 9 | 10,895 | 5% |
| Total | 307 | 228,717 | 100% |

Source: Bartram et al. (1987), p.19.

## Water Treatment Plants

The majority of rural water treatment plants in Peru are centered around the use of slow sand filtration. Most plants also include a sedimentation unit prior to the slow sand filter. The flow scheme of a typical rural water treatment plant in Peru is shown in Figure 3. Note that there are no pumps involved in this gravity-flow system.

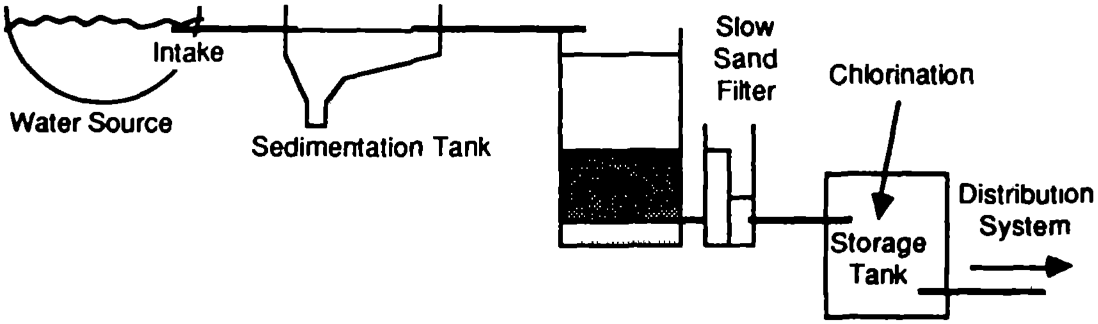
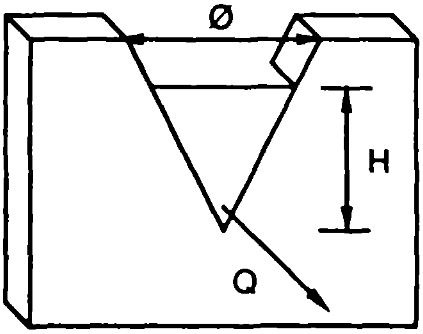


FIGURE 3. Flow Scheme of a Typical Rural Treatment Plant in Peru

### Flow Control

In order for a slow sand filter to operate effectively, its flow rate must not be allowed to vary significantly; unfortunately, most treatment plants in Peru lack effective flow control (Bartram et al., 1987). As a result, in rehabilitating gravity-flow treatment plants, DISABAR has begun to introduce an improved flow rate control mechanism.

The simplified flow control device (Figure 4), as it will hereafter be referred to, consists of a V-notch weir in combination with an overflow weir or spillway. Excess flow passes over the spillway, which serves to set an upper limit on the level of water in the unit. The water level in the V-notch weir determines the flow rate to the rest of the treatment plant according to the following empirical relationship (Huang & Hita, 1987):



$$Q = C\,[\tan(Ø/2)]\,H^{2.5}$$

where

Q = flow rate [cubic meters/second]
H = head on the weir [meters]
Ø = weir angle
C = discharge coefficient, determined by calibration

(?) — depend. on ratio $\frac{a}{b}$ ( $a \gg b$

regulate

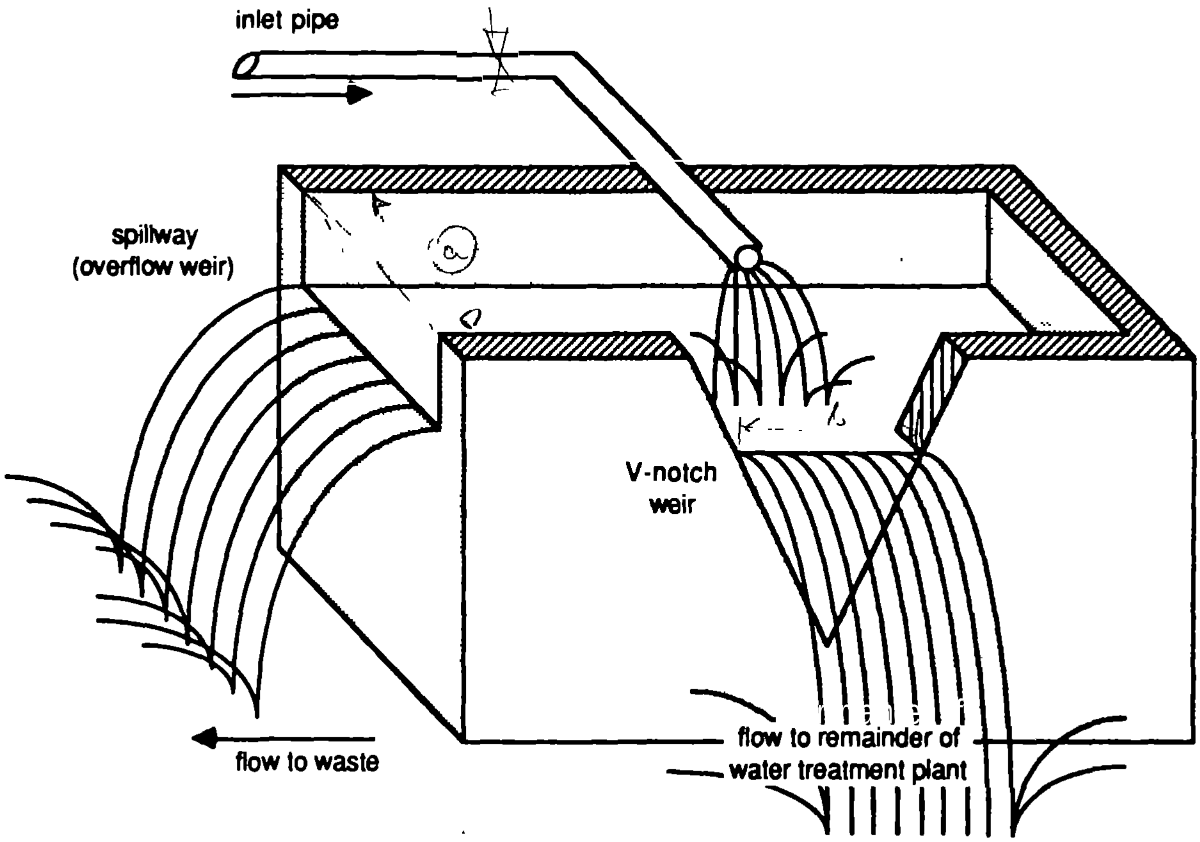


FIGURE 4. Simplified Flow Control Device

The simplified flow control device may be used at different points in the water treatment plant. Placement in the intake structure is the most common, but extra devices may be used at the inlet to a gravel roughing filter or a slow sand filter to ensure a constant flow rate in these units

The main disadvantage of the simplified flow control device is its reduced flow measuring accuracy. However, engineers in Peru have overcome this disadvantage by using a 45° V-notch, which allows for more exact flow measurement and control than a 90° notch because of the smaller variation in flow with a given change in water level. Another disadvantage is the fact that the fixed-level overflow weir sets the flow rate through the V-notch weir permanently. Of course, the V-notch weir can be constructed to allow for adjustment in its level.

## Sedimentation

The sedimentation tanks used in water treatment plants are designed to reduce the concentration of solids enteringthe slow sand filter, but they have proven fairly unsuccessful in this effort, especially under conditions of high influent turbidity. When the raw water has high solids concentrations, sedimentation tanks

tend to fill rapidly with solids, which, because of a lack of routine cleaning, overflow, causing the slow sand filter to clog (DelAqua, 1986).

Part of the problem with the sedimentation tanks in Peru is that they are poorly designed. DISABAR is greatly understaffed and cannot afford to collect important data on the size distribution and settling rates of raw water solids. As a result, the design of sedimentation tanks, normally based on such information, is based on approximate values reported in design manuals instead.

Another common design flaw is the absence of diffusing baffles. Solid baffles force all incoming water to flow underneath them rather than allowing a portion to pass through. This gives rise to sedimentation tank short-circuiting (Figure 5), a phenomenon which renders a portion of the tank volume inactive. Experiments conducted at the water treatment plants in Cocharcas and Palian have shown the effective retention times in their sedimentation tanks to be 13 and 24 minutes, respectively, instead of four hours as designed (Bartram, et al., 1987).

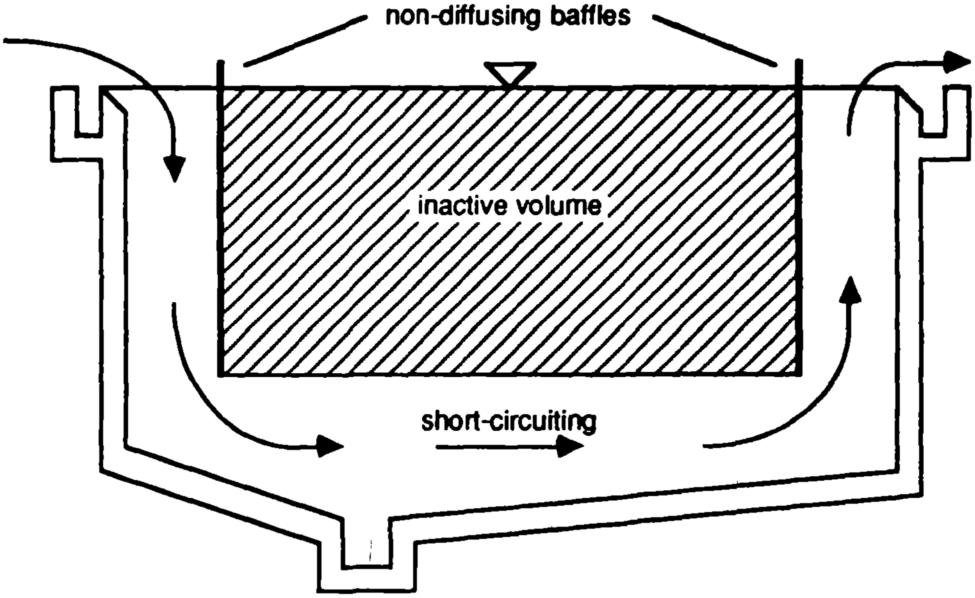


FIGURE 5. Poorly-Designed Sedimentation Tank

In recent years, Peruvian engineers have switched to a different sedimentation tank design, incorporating a baffle which directs water flow through the entire tank cross section (Figure 6). But even if sedimentation tanks are correctly designed, it is questionable whether they will be able to remove a sufficient percentage of solids under high turbidity conditions. A good portion of the suspended solids washed down streams during the rainy season in Peru are slow-settling clay particles that require excessively large sedimentation tanks or the aid of chemical coagulants. Gravel roughing filters (discussed later in this paper) provide a much more efficient solids removal system.

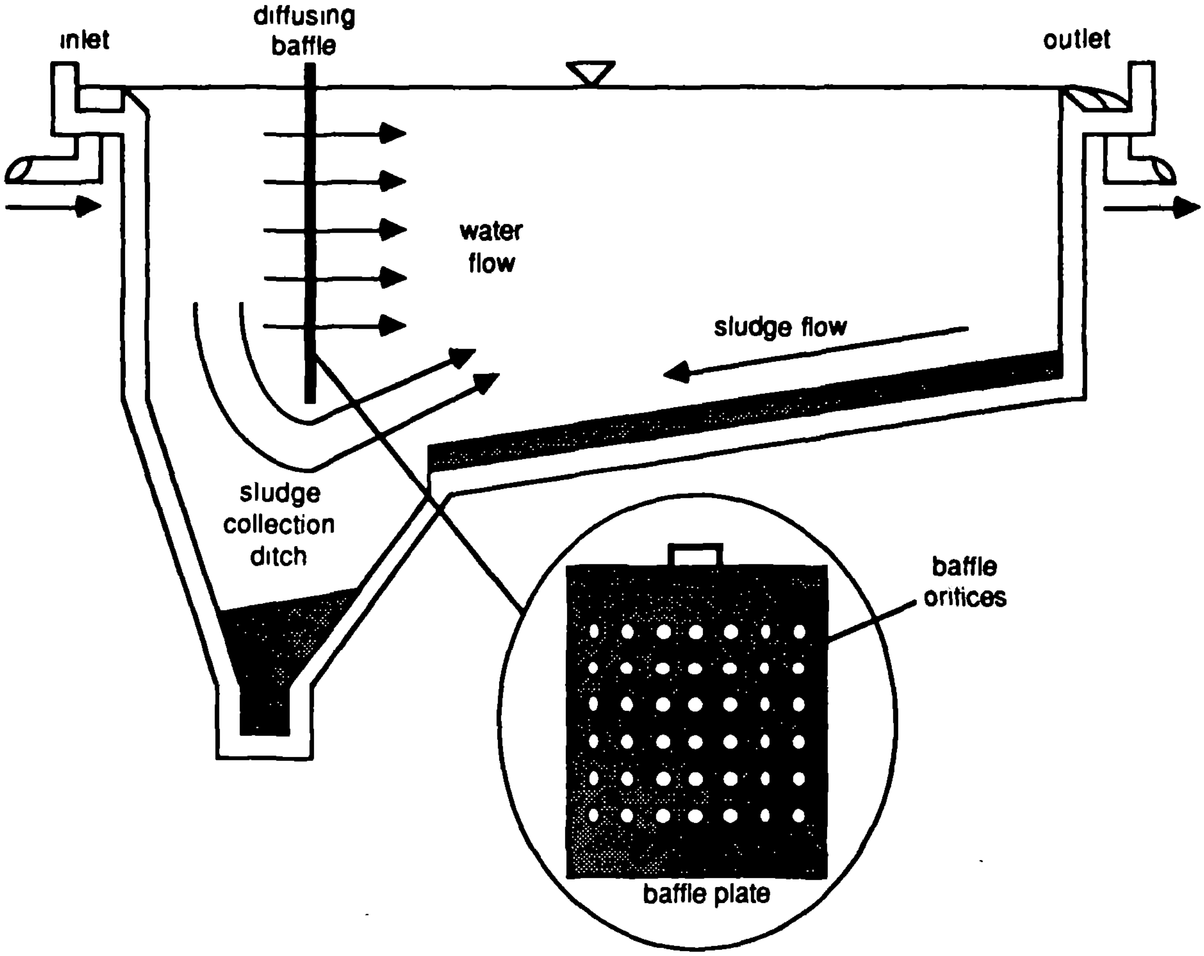


FIGURE 6. Improved Sedimentation Tank

## Chlorination

To guarantee microbiologically-safe drinking water, treatment plants typically provide some form of disinfection. Chlorination is the most commonly used method; it not only kills most pathogens, but also remains in the distribution system in residual quantities to protect against any contamination after treatment.

DISABAR has, in principle, adopted hypochlorination rather than gas chlorination -- which is what is most commonly used in the United States -- as a means of disinfecting drinking water. Hypochlorite compounds, which are available in either solid or liquid form, are much easier to transport and store than chlorine gas ($Cl_2$). Moreover, the technology available for hypochlorite dosing is much less sophisticated than that typically used for its gaseous counterpart.

DISABAR maintains stocks of 30% calcium hypochlorite ($Ca(OCl)_2 \cdot 4H_2O$), a white powder, in its regional offices around the country. The hypochlorite can be

applied to treated water by means of various apparatuses. The most common in Peru is the diffusion hypochlorinator (Figure 7), through which the solid hypochlorite, packed tightly in a perforated cylinder, slowly dissolves into the passing flow of water.

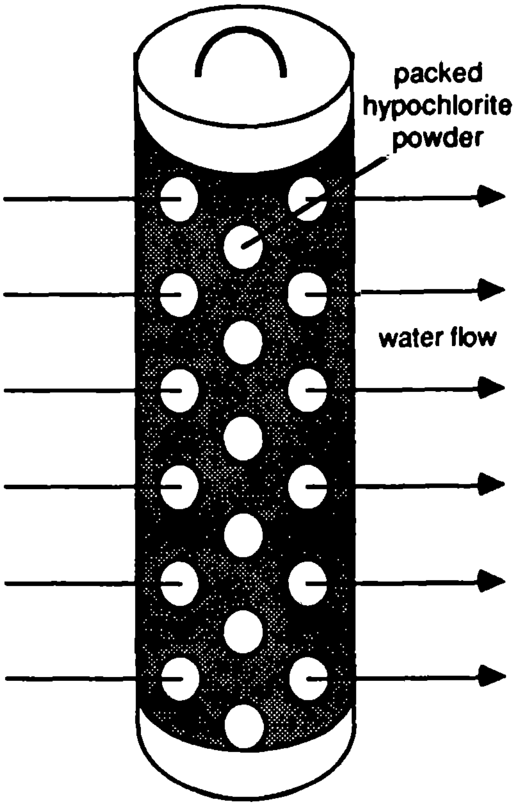


FIGURE 7. Diffusion Hypochlorinator

Another mechanism for hypochlorite dosing is the drip chlorinator (Figure 8). The hypochlorite powder, dissolved in a large container or drum, is fed at a constant rate to the clear water tank. One method of ensuring a constant flow of hypochlorite solution is by means of the floating-bowl device shown in Figure 8. Its inlet maintains a constant depth below the surface of the solution, thus regulating the flow rate.

Despite the availability (in general) of calcium hypochlorite in DISABAR's regional offices and the presence of chlorinating apparatuses at many water treatment plants, drinking water in rural Peru still does not receive proper disinfection. (None of the five treatment plants I visited were effectively disinfecting their treated water.) The main obstacles to proper disinfection are problems with hypochlorite supply logistics and with the operation and maintenance of in-place chlorinating devices. The situation in the Health Ministry's Pilot Region is described as follows by Bartram et al. (1987):

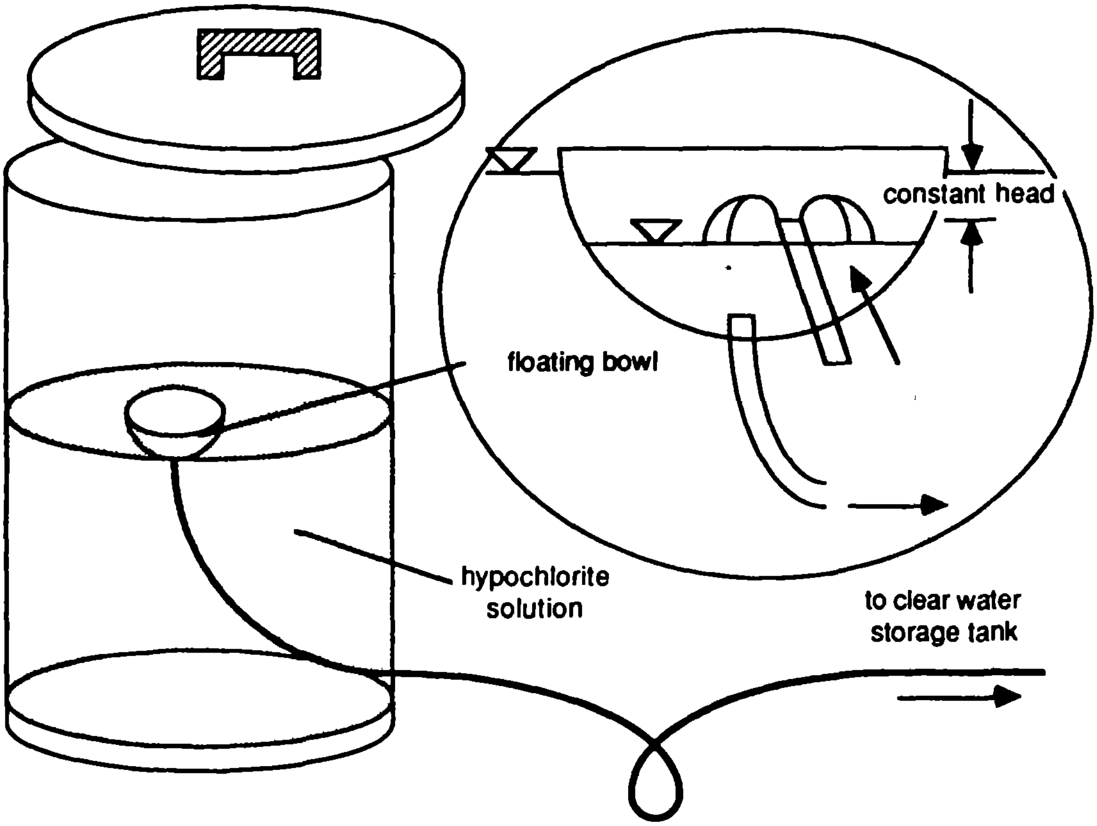


FIGURE 8. Floating-Bowl Type Drip Chlorinator

Only 1% of the communities of the Pilot Region have a stock of chlorine. The only chlorine available to these rural communities is the 30% calcium hypochlorite sold by DISABAR in 2 sites in the region. These sites represent more than a day's travel for some communities and the presence of the hypochlorite is not guaranteed when they arrive. The documentation required to get the powder may then delay half a day and when collected, the powder is loose and difficult to handle. Its storage conditions within the DISABAR infrastructure are severely inadequate. If it has not already deteriorated when collected then it probably deteriorates rapidly in the hands of the communiities who are given no instructions about its handling or storage, and who are very often ignorant about its correct use.

Of the 307 supply systems in [the Department of] Junín, 42% have some type of apparatus intended for continuous chlorination. The great majority of these are DISABAR-promoted [diffusion] "hypochlorinators"... The design is intended to be suspended in a constant laminar flow of 1 litre/sec although it is almost invariably encountered hanging in the corner of the [clear water] reservoir, distant from the inlet or outlet structures and often suspended above the water level, where even when submerged, there is almost no water movement and where it cannot contribute to maintaining water quality...

None of the rural communities of the Pilot Region showed chlorine at any point in the distribution system in sufficient concentration to maintain the hygienic qualities of the water (>0.2 mg/l as free residual).

The absence of effective disinfection in rural areas of Peru -- as well as in most developing countries -- makes effective removal of pathogens in preceding treatment units all the more essential and attests to the importance of slow sand filtration, whose pathogen reduction efficiency (prior to chlorination) is unparalleled by any other filtration system.

## SLOW SAND FILTRATION

Slow sand filtration has been applied extensively in rural areas of Peru and -- when functioning properly -- has proven to be an effective treatment system for the removal of disease-causing organisms. It is cheap, simple to operate and maintain, and also has the advantage of using mainly locally-available materials.

Unfortunately many slow sand filters have failed to produce expected results. A report by DelAqua (1986) states that 16 of 16 slow sand filters evaluated in the central highlands and high jungle of Peru present "major deficiencies and operating problems." Bartram et al. (1987) reports that in the Department of Junin, 76% of the 25 existing slow sand filters supply grossly contaminated water. Some of the main problems causing the poor performance of slow sand filters in rural Peru are discussed below (based in part on Bartram et al., 1987 and DelAqua, 1986).

(1) <u>High Influent Turbidities</u> -- During the dry season in the Sierra, turbidity in streams is usually about 10 NTU, but during the rainy summer months of December to March when heavy flows wash high sediment loads down streams, raw water turbidities may reach 500 to 2000 NTU. Under these conditions, sedimentation tanks cannot remove solids rapidly enough to prevent the clogging of slow sand filters. The ability of slow sand filters to cope with high influent turbidities is one of the main challenges facing the widespread adoption of this system by water supply planners in developing countries.

(2) <u>Faulty Design and Construction</u> -- Many slow sand filters in Peru have been designed or constructed with the following flaws: a) incorrectly graded filter bed sand or support gravel (see Appendix); b) inadequate or absent flow control (which leads to intermittent operation and irregular filtration rates); c) lack of a minimum head mechanism to prevent the drying out of the filter bed; d) lack of a means to protect the sand surface "schmutzdecke" from disruption by incoming raw water; e) smooth filter walls which allow short-circuiting of water past the filter bed.

(3) <u>Poor Operation and Maintenance</u> -- Despite the simplicity of slow sand filters, their operation and maintenance is still too complicated for caretakers with little or no technical training. In many rural villages no caretaker is even hired because water usage fees are not collected, and since DISABAR is constrained by scarce financial and human resources, it cannot be counted on to provide regular support.

To address these problems, Peruvian engineers, with the aid of foreign experts, have made two major modifications to conventional slow sand filtration:

(1) As a means of simplifying the operation and maintenance of slow sand filters, Peruvian engineers developed and what they call the "modified slow sand filter."

(2) To reduce the high influent turbidities, DISABAR recently adopted the use of pretreatment by gravel roughing filtration.

These improvements, discussed in the following two sections, are important steps in the adaptation of slow sand filtration to conditions in Peru. They may also prove useful in reducing constraints on its use in other areas of the world.

## The Modified Slow Sand Filter

Despite its overall simplicity, the slow sand filter, as traditionally designed (Figure 9), has features that require operational efforts often beyond the technical capacity of small, rural communities in developing nations.

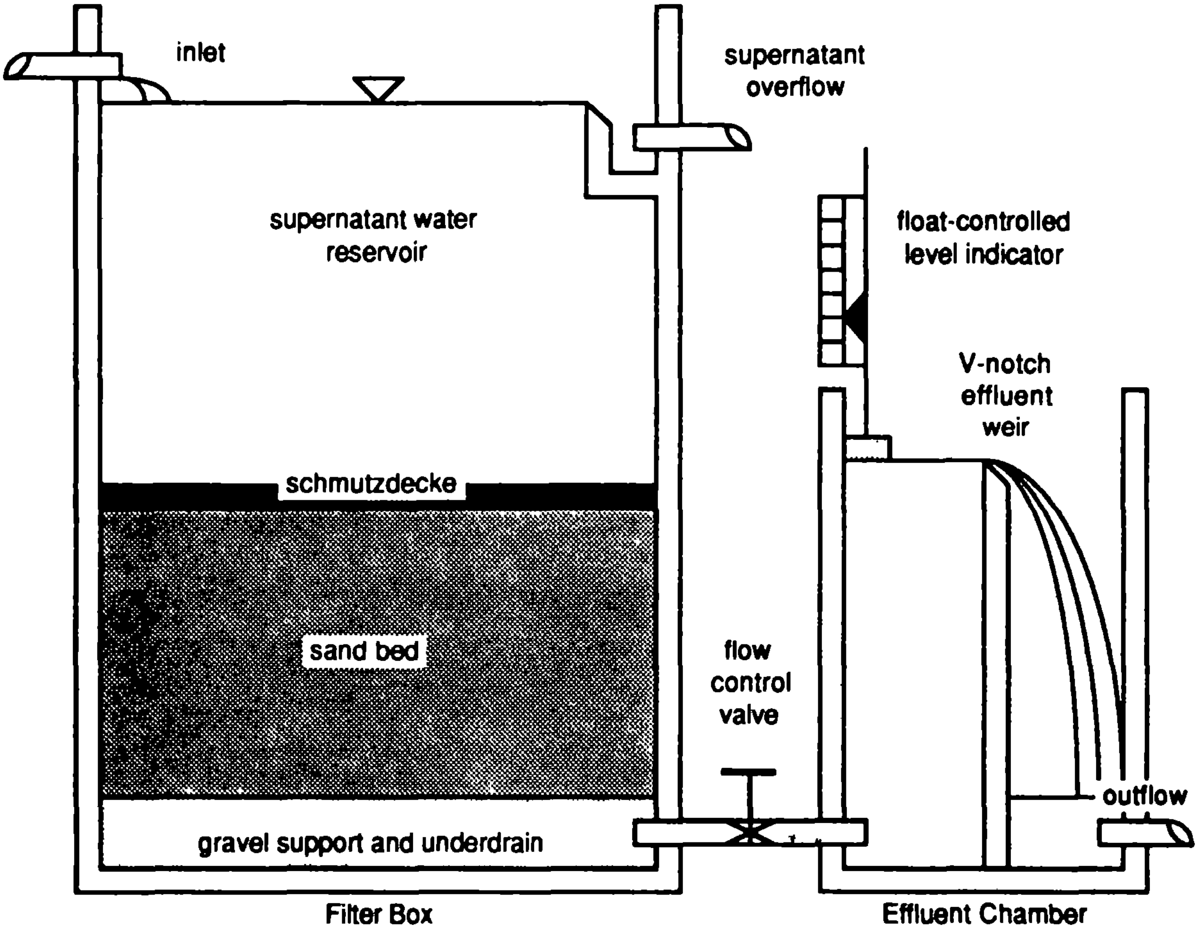


FIGURE 9. The Classical Slow Sand Filter

One of the classical slow sand filter's most complicated features is its flow control system, whose main component is a flow control valve located on the pipe that carries the filter's effluent from the filter box to the effluent chamber. The purpose of this valve is both to control the rate of filtration and to maintain the supernatant water reservoir at a constant level (usually 1.0-1.2 meters above the top of the sand bed). To maintain a constant filtration rate -- which is crucial to the success of slow sand filtration -- the flow control valve must be adjusted on a daily basis according to the readings on a flow measuring device (either a Venturi meter or a V-notch weir in conjunction with a float-operated level indicator).

At the beginning of a filter run (just after cleaning), the sand bed offers the least amount of resistance to water passage. The flow control valve is opened only slightly, thus furnishing the extra head loss that accounts for the height of the supernatant water above the effluent weir. As the filter run progresses, an increasing proportion of the head provided by the supernatant water is lost in the increasingly-clogged sand bed, requiring that the head loss in the control valve be gradually diminished in compensation (Figure 10). The filter run reaches it end when the valve is completely open and the head loss in the sand bed no longer permits the filter to pass water at the designed filtration rate. At this point the sand bed must be cleaned in preparation for a new run.

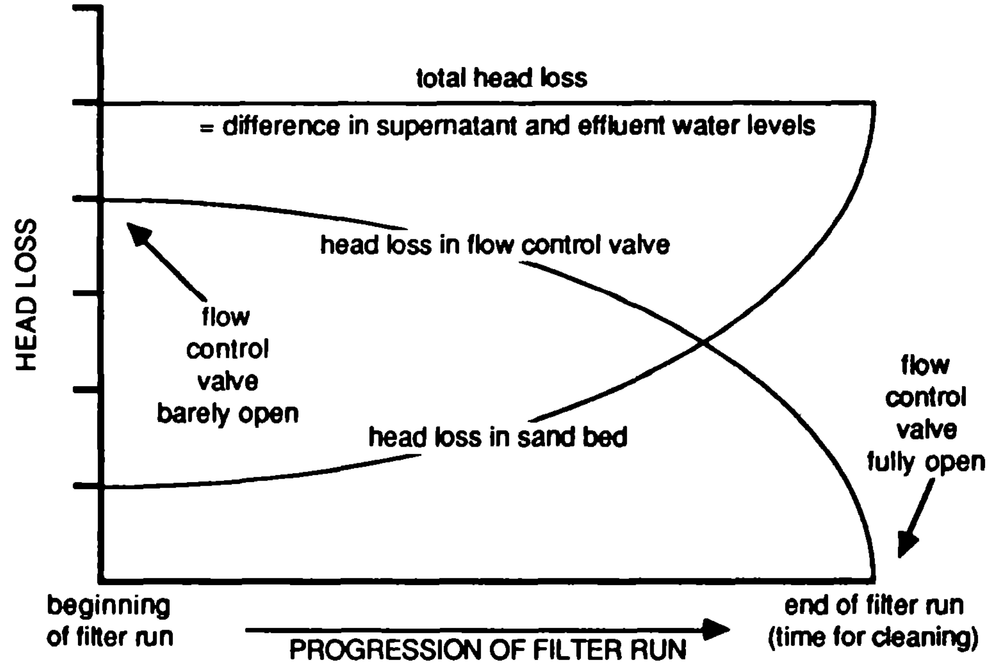


FIGURE 10. Head Losses in the Classical Slow Sand Filter

In rural villages, the daily checking of the filtration rate and adjustment of the flow control valve is often a task which requires either a greater level of technical competence or a greater frequency and regularity of monitoring than can be

counted on. In order to reduce the operational complexity of the slow sand filter, Peruvian engineers developed what they refer to as the modified slow sand filter (Figure 11 -- see also Pérez & Vargas, 1984 ).

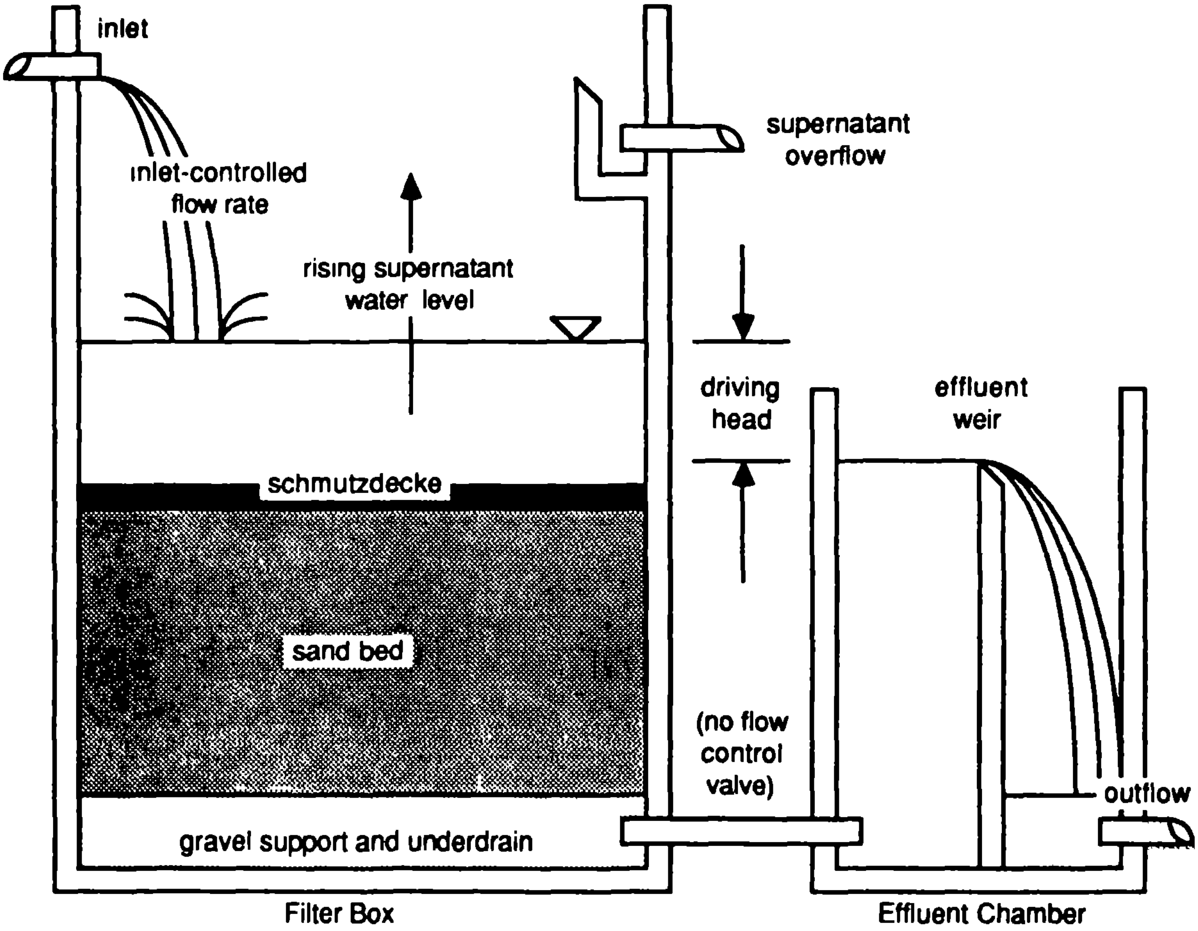


FIGURE 11. The Modified Slow Sand Filter

The modified slow sand filter eliminates the flow control valve and the flow measuring device at the effluent end, replacing them with the simplified flow control device (discussed earlier in this report under "Flow Control"-- see Figure 4) at the influent end. The advantages of the simplified flow control device over the flow control valve are its greater simplicity of operation and reduced monitoring requirements; it renders the operation of the slow sand filter (as well the rest of the treatment plant) virtually automatic without introducing any complicated mechanical parts. (It should be noted, however, that the simplified flow control device can only be used in gravity-flow systems; in pumped systems, other means of controlling the inlet flow rate on the modified slow sand filter are required.)

In addition to changing filter operation from outlet- to inlet-controlled, the modified slow sand filter also operates with an increasing rather than a constant

supernatant water level. This is necessary because, unlike the classical slow sand filter, the modified version has no flow control valve to make up the difference between the head provided by the supernatant water and that consumed in the filter bed.

At the beginning of a filter run, the level of the supernatant water is at the minimum set by the effluent weir. As water begins to flow into the filter, the water level rises slightly above the level of the effluent weir, providing the difference in head needed to induce flow through the filter bed. During the course of a filter run, the head loss in the filter bed increases, causing the supernatant water level to rise in order to supply the additional head required to maintain the same filtration rate (Figure 12). The end of the filter run is signalled when the supernatant water level reaches its maximum height and begins to drain into the supernatant overflow.

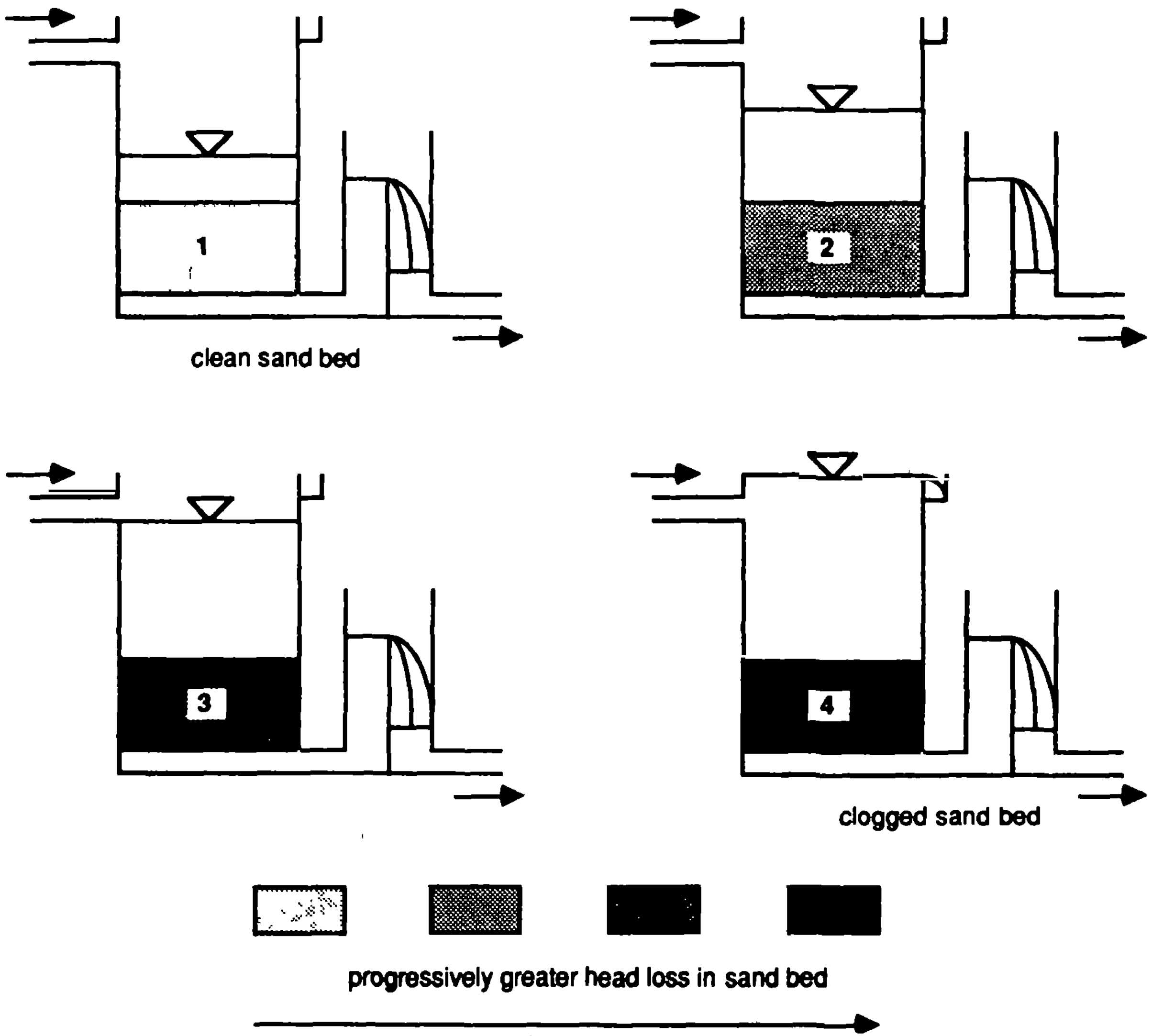


FIGURE 12.
Variation of Supernatant Water Level Over the Course of a Filter Run in the Modified Slow Sand Filter

The use of an increasing rather than a constant water level may have some disadvantages. According to Huisman and Wood (1974), maintaining a constant supernatant water level is preferrable for the following reasons:

(1) it reduces the danger of disturbing the schmutzdecke;
(2) it enables floating impurities to be removed from the supernatant reservoir through fixed scum outlets;
(3) it prevents deep penetration of sunlight which might encourage growth of rooted aquatic plants of the filter surface.

The sacrifice of these benefits may, however, be a small price to pay for the great increase in simplicity offered by the modified slow sand filter.

Visscher et al. (1987) have likewise observed that a rising water level complicates the removal of floating scum and algae, but have also noted that it provides a simple indicator of the degree of filter clogging. What remains to be determined, according to these authors, is whether the low retention time at the beginning of a filter run (due to the low initial supernatant water level) affects the ripening process.

## The Gravel Prefilter

To deal with the problem of excessive raw water turbidity and slow sand filter clogging, DISABAR has begun to include an extra treatment unit in the design of new water treatment plants and the rehabilitation of old ones (Figure 13). The new unit involves pretreatment by gravel roughing filtration of water entering the slow sand filter.

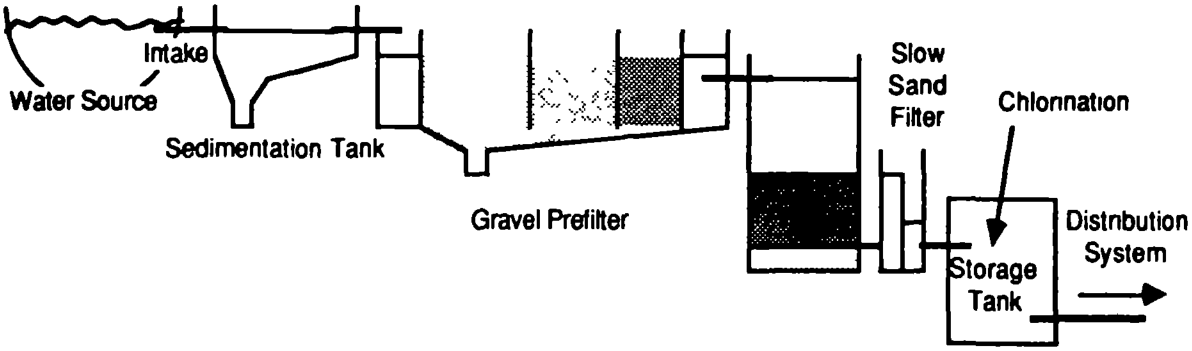


FIGURE 13. Flow Scheme of Upgraded Treatment Plants

The mechanism by which these gravel prefilters (as they are called in Peru) remove turbidity from raw water is akin to sedimentation; as the water passes through a multitude of small pore spaces, solid particles settle on the surface of gravel rocks. According to Wegelin (1986):

> The (gravel roughing) filter acts as a multi-stage sedimentation basin, thus providing a large surface area for the accumulation of settleable solids. The solids accumulate on top of the collectors and grow into dome-shaped aggregates with advanced filtration time. Part of the small heap drifts towards the filter bottom once the heaps reach instability. This drift regenerates the filter efficiency of the upper gravel layers and enables accumulation of a considerable amount of retained material.

Once the solids have filled up all the pore spaces, which afford a considerable volume of storage space, the gravel bed must be cleaned. In Peru, the cleaning of gravel prefilters is carried out hydraulically. Prefilter boxes are built with extra freeboard on the top wall, allowing the water level to be increased prior to washing. When the water level has reached a maximum level, wash gates at the bottom of the prefilter are opened and the water, passing rapidly down through the gravel, washes out the solids collected in the pore spaces. It is important that the cross-sectional area of the wash channels be large enough to allow for the high flow rates needed to produce sufficient scouring action.

Prefilters in Peru are equipped with hydraulic wash gates designed to open rapidly in order to take maximum advantage of the high initial head of water in the filter bed (Figure 14). One problem DISABAR engineers have had in designing the wash gates is that of ensuring their watertightness during normal operation. (The wash gates on both of the prefilter units I saw during my treatment plant visits were propped shut with wooden sticks to avoid water leakage.) Preventing leakage through the gates is difficult because of the high water pressure at the bottom of the filter.

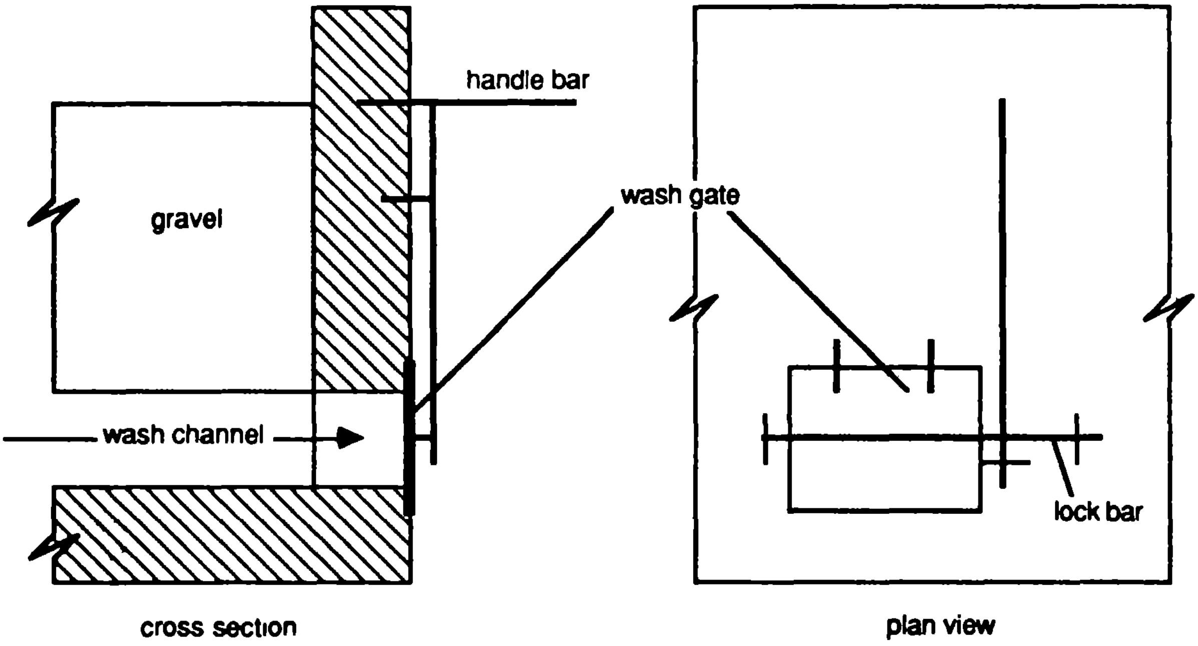


FIGURE 14. Rapid-Opening Prefilter Wash Gates
Source: DelAqua (1986), p.30

In Peru there are two variations of the gravel prefilter currently in use: the vertical- and horizontal-flow roughing filters (Figures 15 & 16). Both versions consist of a series of filter sections (generally three or four) of different gravel sizes (decreasing in the direction of water flow). The horizontal-flow prefilter has the advantages of allowing unlimited filter length whereas in the vertical-flow prefilter, the depth of each section is limited by the difficulty of constructing below a certain depth (Wegelin, 1986). The horizontal-flow version also has simpler construction features and requires only one wash gate, whereas the vertical-flow prefilter requires a wash gate for each section.

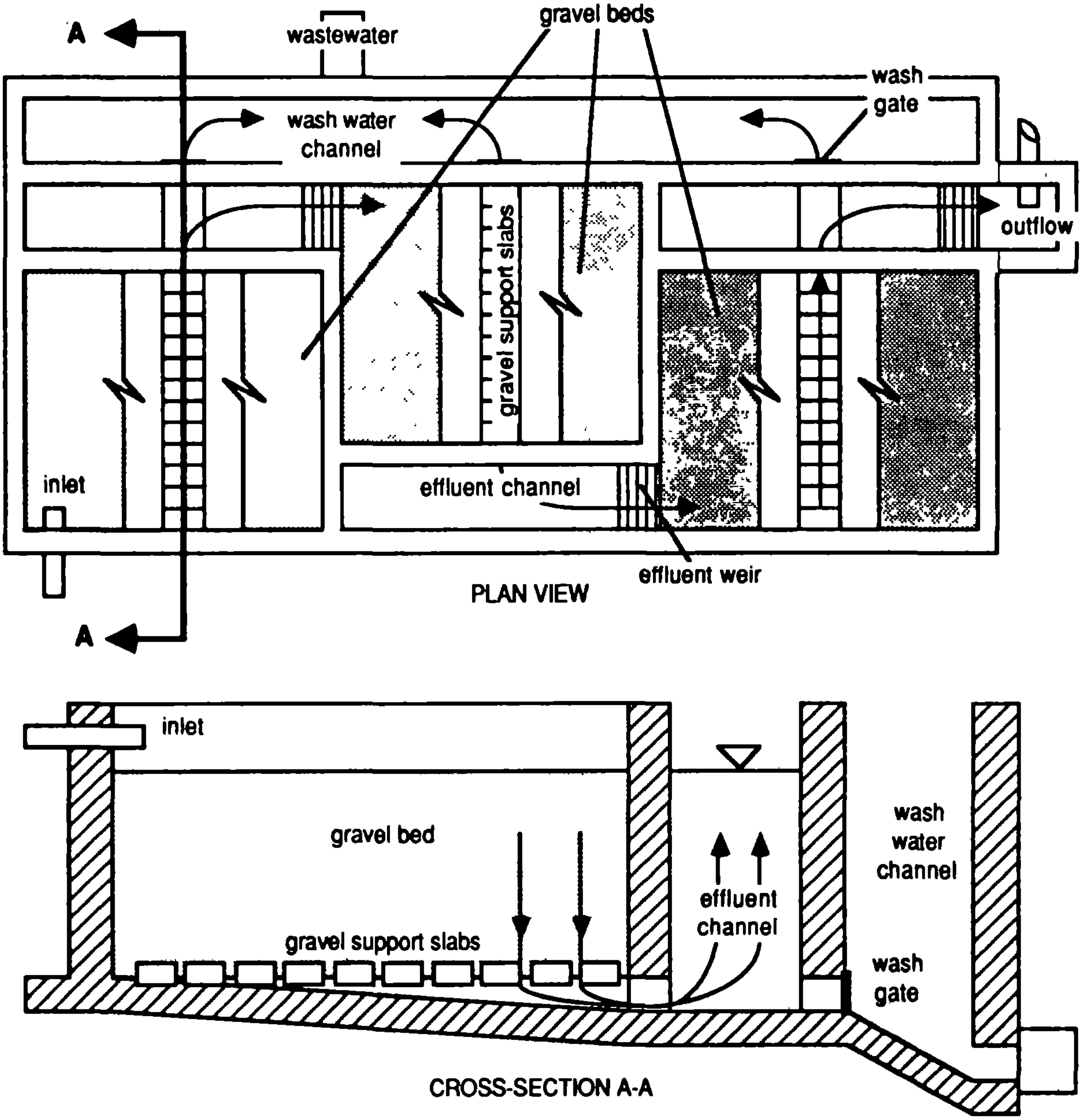


FIGURE 15. Vertical-Flow Gravel Prefilter

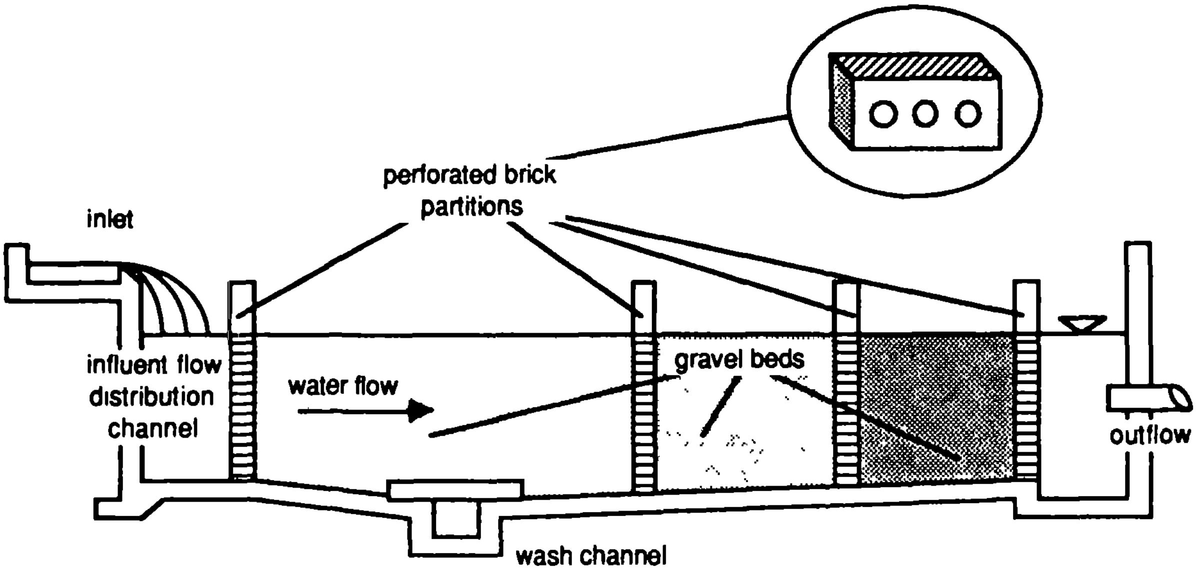


FIGURE 16. Horizontal-Flow Gravel Prefilter

The combination of gravel prefilter and slow sand filter is quite effective. The gravel prefilter provides the physical removal of solids the slow sand filter cannot handle, and the slow sand filter provides subsequent biological treatment to bring the bacteriological quality of the water to acceptable drinking water standards (Wegelin, 1986).

Experiments carried out by Pardón (1987) on the vertical-flow gravel prefilters in San Vincente de Azpitia show that they are capable of very high turbidity removal efficiencies (Table 5). The removal efficiencies actually increase (from 62% to 92%) with increasing influent turbidity.

Of course, the real measure of a pretreatment system's success is its ability to prevent slow sand filter clogging. Pardón reports that under the protection of prefilters, Azpitia's slow sand filters only had to be taken down for cleaning three times (with consecutive filter runs of 16, 13, and 26 days) during the period of January 5 to March 20, 1986, which coincides with the heavy rain season in Peru. While under normal conditions slow sand filters can usually run for several months without cleaning, Huisman and Wood (1974) state that the minimum length of a filter run under the worst raw water quality conditions should be two weeks. Based on this criteria, Azpitia's prefilters can be considered successful.

Table 5 shows that gravel prefilters are also capable of fairly high fecal coliform reductions (70%). This has generated speculation that gravel roughing filtration may involve biological, in addition to physical, treatment (Wegelin, 1986). This hypothesis remains untested -- and perhaps relatively unimportant as long as the prefilter is followed by an effective biological filtration system. Still, there is talk

## TABLE 5
## Turbidity and Fecal Coliform Removal Efficiencies of the Water Treatment System of San Vincente de Azpitia
## (Evaluation Period: January-March, 1986)

| Treatment Step | Turbidity (NTU) Ranges | | | | | | Fecal Coliforms (#/100 ml) | |
|---|---|---|---|---|---|---|---|---|
| | 20-100 | | 100-300 | | 300+ | | | |
| | effl. | %red. | effl. | %red. | effl. | %red. | effl. | %red |
| Canal | 70 | - | 228 | - | 915 | - | 690 | - |
| Presedimentation | 49 | 20 | 184 | 16 | 548 | 39 | 690 | 9 |
| Gravel Prefilter | 17 | 63 | 37 | 79 | 45 | 92 | 156 | 70 |
| Slow Sand Filter | 4 | 76 | 6 | 83 | 5 | 89 | 15 | 90 |
| Global Treatment | - | 94 | - | 97 | - | 99 | - | 97 |

effl. = average effluent turbidity or coliforms from that treatment step
% red = percent change between the influent and effluent of that step

Source: Pardón (1987), p. 41

among DISABAR officials of further testing the ability of the gravel prefilters to reduce pathogens to acceptable standards on their own. The elimination of a need for slow sand filtration could further decrease the cost and complexity of rural treatment plant design, construction, and operation.

In any case, gravel roughing filtration holds much promise in helping to solve the problem of high influent turbidity, which hinders the widespread application of slow sand filtration. Just as the slow sand filter, the gravel roughing filter is ideally suited for application in developing countries; it is inexpensive to build, simple to operate, maintain, and clean, and is constructed of materials which are usually available either locally or nationally.

# SITE VISITS

During my trip to Peru I visited five rural water treatment plants. Four of these were in rural communities in the province of Huancayo, the other was in the village of San Vincente de Azpitia about 100 kilometers south of Lima. This section of the report is dedicated to a brief description of each of these water supply systems.

## The Province of Huancayo

Huancayo is a city of about 200,000 inhabitants 312 kilometers east of Lima and high up in the Andean Sierra -- about 3500 meters above sea level (see Figures 1 & 2). Huancayo is situated in the very fertile Mantaro valley which lies between the two *cordilleras* of the Andes. Despite the fact that the Mantaro valley produces a large proportion of Peru's agricultural output (corn, wheat, potatoes and Lima beans) and the distribution of land has been fairly egalitarian since the land reform which followed the military coup of 1968, Huancayo and the surrounding communities still suffer much poverty, poor health conditions and a shortage of such essential public services such as water supply, health care, and education. At the same time, Huancayo is one of Peru's most developed provinces.

One of DISABAR's 23 regional offices is in Huancayo. It has a small laboratory equipped to carry out water quality analyses; a storage depot for construction material and other supplies (including calcium hypochlorite); and offices where engineers design water supply systems for the local communites. The regional office works directly with communities in the province of Huancayo, providing skilled labor, materials, and supervision for construction; financial, technical and logistic support; and periodic inspections (once or twice a year) of water system performance. The communities receiving water supply systems are responsible for organizing themselves by setting up a local water board, appointing a caretaker and financing operation and maintenance costs by collecting water usage fees. The community usually also provides unskilled labor during construction.

Most of the approximately 200 water supplies in the Huancayo area take their water from springs; only about 10 of these systems use surface water. The groundwater level in the most of the province is fairly close to the ground surface (4 to 5 meters below ground) and the only reason it is not used in all water systems is that DISABAR wants to avoid the use of pumps wherever possible. Communities situated too far from springs are, therefore, forced to use surface water.

As mentioned, I visited four rural villages in the vicinity of Huancayo. Three of these have surface water supply systems and one has recently converted from surface water to a spring source. All four communities have slow sand filtration plants, but only two were in operation; another was under construction and the fourth has been abandoned altogether. Each of these water supply systems is discussed in one of the following four sections.

## San Agustín de Cajas

The slow sand filtration plant at San Agustín de Cajas is in full operation, but is functioning very poorly. San Agustín's water system consists of a very crude intake, a poorly designed sedimentation tank, and two heavily overloaded slow sand filters.

The main problem with the system is that it has no flow control mechanism. The intake simply consists of a ditch with a coarse wire mesh screen set on the side of the canal that functions as the plant's water source. The flow rate into the plant is controlled only by the level of water in the canal and is therefore subject to great variation. A varied flow rate through the plant causes undesirable fluctuations in the filtration rate of the slow sand filter, thus reducing its effectiveness.

The sedimentation tank at San Agustín has two baffles designed to isolate the central segment and create the quiescent conditions necessary for settling to take place. However, the baffles have no orifices and force all entering water to pass below them (see Figure 5). This produces short-circuiting of the sedimentation tank as described earlier in this report (see "Sedimentation").

The 20 year-old slow sand filters at San Agustín are of the modified rather than classical variety, indicating that modified slow sand filtration has been practiced for a long time in Peru. Aside from the lack of flow control, the main problem with the slow sand filters is that they are overloaded with solids. The turbidity and brown color of the supernatant water testify to the need for pretreatment to reduce influent solids concentrations. DISABAR is presently considering upgrading the San Agustín plant to handle high turbidity by converting the sedimentation tank into a gravel prefilter.

In addition to turbidity problems, San Agustín's slow sand filters are plagued by a series of design and construction flaws. There is no slab below the influent weir to protect the sand surface from disruption by incoming water when the supernatant water level is low. This problem is compounded by the fact that the weirs which distribute the incoming flow along the width of the two slow sand filters were not constructed perfectly horizontal and most of the flow passes over the weirs within a small width.

Also, like most slow sand filters, San Agustín's have effluent weirs designed to

set a minimum water level in the filter, but the effluent weir chambers are uncovered, exposing treated water to contamination. This is especially dangerous since the plant lacks final disinfection. (Each of the two effluent chambers is equipped with a diffusion hypochlorinator, neither of which contained any hypochlorite powder at the time of my visit).

## Cocharcas

The water treatment plant at Cocharcas (pop. 624, $Q_{avg} = 103$ m$^3$/d) was recently upgraded from a standard slow sand filtration plant to include pretreatment for high influent turbidity by horizontal-flow gravel prefiltration. The details of the rehabilitation project carried out there are discussed in a report by DelAqua (1986). I would like to add a few comments based on observations made while visiting the plant.

Despite its recent rehabilitation, the Cocharcas plant still has design deficiencies and operational difficulties (though these are not as serious or fundamental as those of the San Agustín plant). One problem (immediately evident as I entered the plant) was the overflowing sedimentation tank. The reason for this is not clear, but I suspect it is related to the fact that the actual flow rate entering the gravel prefilters was below its design flow rate (the water level in the simplified flow control unit preceding the prefilter was below the level of the overflow weir). The combination of an excessively high water level in the sedimentation tank and a reduced flow rate entering the prefilters leads me to believe that there was excessive head loss in the piping connecting the two units. Unfortunately I was not in the position to verify this hypothesis.

Another problem at the Cocharcas plant is that of air blocks in the transmission line between the intake and the sedimentation tank. When the inlet valves to the sedimentation tank are opened, air bubbles are forced through the piping and up to the surface of the tank. A series of 90° bends in the transmission mains seems to be the source of this problem.

Aside from the problem with sub-design flow, the new horizontal-flow gravel prefilters (see Figure 16) are functioning without major difficulties. The difference between the turbidity of the water entering the slow sand filters in Cocharcas and San Agustín is quite noticeable and demonstrates the effectiveness of the Cocharcas's prefilters. The only other defect in the prefilters is that of water leakage from the wash gates. In order to reduce the loss of water, the gates have been propped shut with logs.

The slow sand filters at Cocharcas are also functioning well, mainly due to the protection from solids overloading afforded by the prefilters. Both the filters and prefilters only need to be cleaned about twice a year now that the pretreatment unit has been installed. The floating masses of algae on the slow sand filters, due to

the absence of a scum removal mechanism, apparently do not present any problems of clogging.

Like the slow sand filters at San Agustín, those at Cocharcas are of the modified variety. The only significant difference is in the design of the minimum water level control mechanism; instead of using an effluent weir, as most slow sand filters do, the filters at Cocharcas employ a system of effluent pipes (Figure 17). The piping includes an opening at its highest level designed to reestablish atmospheric pressure and avoid siphoning of water from the filter.

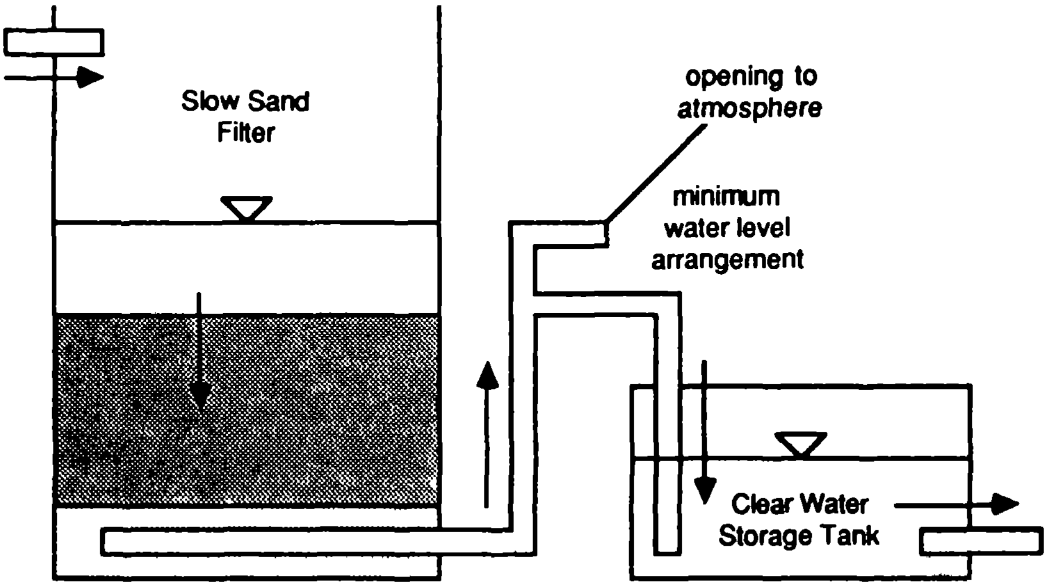


FIGURE 17. Cocharcas's Slow Sand Filter

The flow rate through the slow sand filters is the same as that leaving the gravel prefilters; it is controlled by the same flow control unit which regulates flow through the prefilters. There is a valve between the prefilters and the filters used to fill the prefilters to a high water level before washing and at the same time to cut off flow to the filters when these are being drained in preparation for cleaning. This valve's dual function is somewhat problematic because it requires that regular operation cease when any one of the filters or prefilters are being cleaned. A more logical arrangement would allow any unit to be taken out of service without hindering the operation of others.

Like the San Agustín plant, Cocharcas's water supply system is equipped to provide final disinfection, but, again, the chlorinating apparatus, a floating-bowl type drip chlorinator (see Figure 8), was inoperative at the time of my visit. The calcium hypochlorite had come out of solution and settled at the bottom of the trash can-like plastic container from which it is dosed into the clear water storage reservoir. The hypochlorite was clogging the intake to the flexible plastic hose, which had also sunk to the bottom of the container. Because the plastic tube was

clogged, the storage reservoir was receiving no chlorine dosage.

The main source of problems at Cocharcas's treatment plant is the lack of proper operation and maintenance. The community of has failed to demonstrate full support and cooperation for the rehabilitation project and has not organized itself since the project was implemented. Consequently, the plant does not receive the regular attention of a paid operator. One of the reasons for the lack of support for the rehabilitation project is that Cocharcas has already experienced the failure of its water supply system and the inhabitants are not as enthusiastic as those in communities who are receiving a water supply system for the first time.

### Palian

At the time of my visit, the water treatment plant at Palian (pop. 1815) was in the process of being rehabilitated. The old system consisted of a single unit which contained a grit removal chamber, a sedimentation tank, and one slow sand filter. The plan for rehabilitation includes upgrading the intake, installing a new transmission line, adding two gravel prefilters, and splitting the slow sand filter into two units with a wall down the middle.

The sand in the slow sand filter is being replaced because it was too fine. The perforated PVC underdrains are also being replaced with a brick underdrain system. Another construction flaw which needs to remedied is the smooth surface of the slow sand filters' walls, which encourages short-circuiting of the filter bed.

### Hualhuas

At Hualhuas, surface water treatment has been abandoned altogether in favor of spring water. The slow sand filtration system had been plagued with the same problems which have forced DISABAR to implement rehabilitation projects at other plants.

At Hualhuas changing to spring water was considered much simpler than upgrading the water treatment plant. The capital cost involved in constructing spring water supplies is often greater than the cost of constructing or rehabilitating water treatment plants, but in the long term, the savings in operational costs, the simplicity of operation, and the far superior quality of water produced frequently make spring water supplies the most desirable option.

## San Vincente de Azpitia

Azpitia is a small rural community of 486 people situated about 100 kilometers south of Lima on the Pacific Coast (see Figure 1). Azpitia's water supply system (its first) was built only recently (construction was finished in January 1985), but its performance has so far been notably superior to that of most rural systems in Peru. One reason is that, in contrast with other communities, Azpitia is very well organized. Azpitia has commissioned a water supply authority which collects 15 Intis ($0.15) per household on a monthly basis to pay for operation and maintenance of the system. The fee is used, in part, to hire a caretaker at 800 Intis ($8.00) per month.

TABLE 6
Details of Azpitia's Water Supply System

| | |
|---|---|
| Actual Population | 486 |
| Design Period | 15 years |
| Population Growth Rate | 3% per year |
| Design Population | 730 |
| Per Capita Flow Rate | 40 litres/cap/day |
| Average Flow Rate | 29.2 cubic meters/day |
| Max Daily Flow Rate | 35.0 cubic meters/day |

| | |
|---|---|
| Source | Azpitia Canal; Avg. Flow: 150-250 litres/sec |
| Intake | simplified flow control device; Q= 0.4 litres/ sec |
| Grit Removal | retention time = 1.6 hours |
| Gravel Prefilter | vertical-flow; filtration rate =0.3 meters/hr |
| Slow Sand Filters | 4 prefabricated units; filtration rate = 0.15- 0.20 meters/hr |
| Disinfection | calcium hypochlorite dosing; not effectively practiced |
| Storage | 12 small asbestos-cement tanks; total vol = 12 cubic meters |
| Distribution | 12 public standposts |

Source: Pardón (1987), p.22

The source of Azpitia's water is a small canal, built in 1901, which runs through the village and is used to irrigate the local farmlands. The canal, in turn, derives its water from the Rio Mala, which passes about 30 meters below Azpitia (Figure 18). To avoid pumping, the canal taps into the river far upstream of the community, where the river's elevation is sufficient to allow gravity flow. Azpitia's water supply system, like most others in Peru, is powered exclusively by gravity.

The water from the canal enters the water supply system through a simplified flow control unit. The first treatment step is a small sedimentation tank which functions mainly as a grit chamber. Azpitia's sedimentation tank includes the improved (diffusing) baffles discussed earlier in this report (see "Sedimentation").

The sedimentation tank is followed by a three-step vertical-flow gravel prefilter (see Figure 15). This pretreatment system,, installed as part of a project sponsored by the Pan-American Center for Sanitary Engineering and Environmental Sciences (CEPIS) and the Peruvian Ministry of Health, is the first of its kind in Peru. (For more details, see Pardón's thesis (1987) for the Universidad Nacional de Ingenieria.)

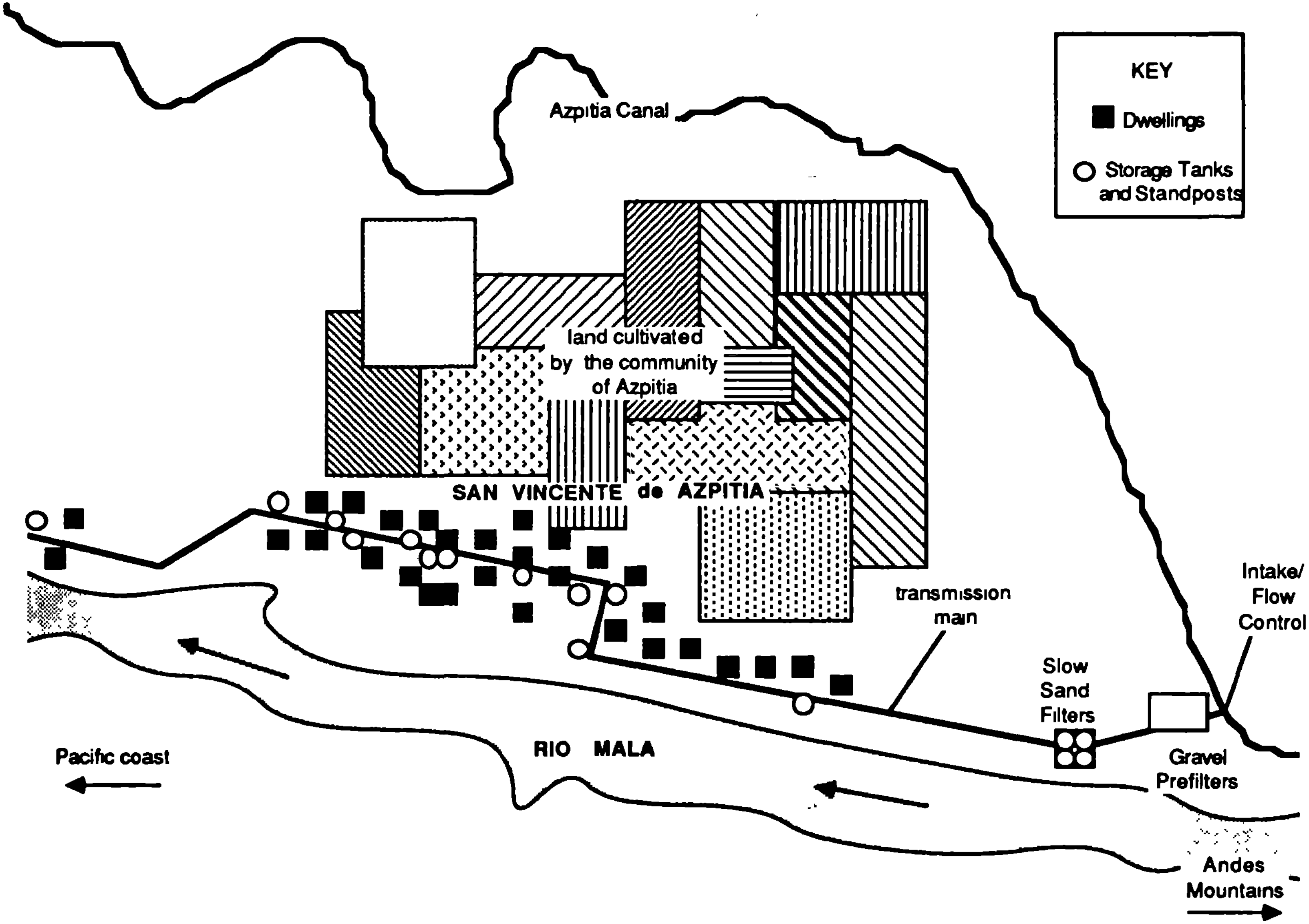


FIGURE 18. Map of San Vincente de Azpitia and Its Water Supply System

Source: Pardón (1987), pp. 20 & 23

Like other gravel roughing filters in Peru, Azpitia's vertical prefilter is designed to remove solids prior to slow sand filtration. Water flows downward through a gravel bed which collects the solids and then up into an effluent chamber from which it overflows into the next prefilter segment. The prefilter is washed hydraulically with one wash gate per segment.

One problem with Azpitia's prefilter is that there is only one unit; therefore, when one of the segments is taken down for cleaning, the prefilter must be by-passed to allow continuous operation. Because of the low flow rate, a prefilter segments takes about six hours to refill and reenter into operation after cleaning. This implies that cleaning must be limited to times of low raw water turbidity, when pretreatment is not needed.

The next step in Azpitia's water treatment plant is the slow sand filtration system which consists of four prefabricated plastic filter units (Figure 19) that are part of a package water treatment plant developed for use in rural communities by DelAqua Ltd. of Great Britain. (For more details see Lloyd et al, 1986.) DelAqua refers to the prefabricated filters, which resemble large trash cans, as protected slow sand filters (PSSFs) because each unit is equipped with two or three mats of synthetic fabric (placed on the surface of the filter sand) designed to provide coarse prefiltration and protect the sand from heavy solids loading. These mats can be removed from the filter and cleaned by hand.

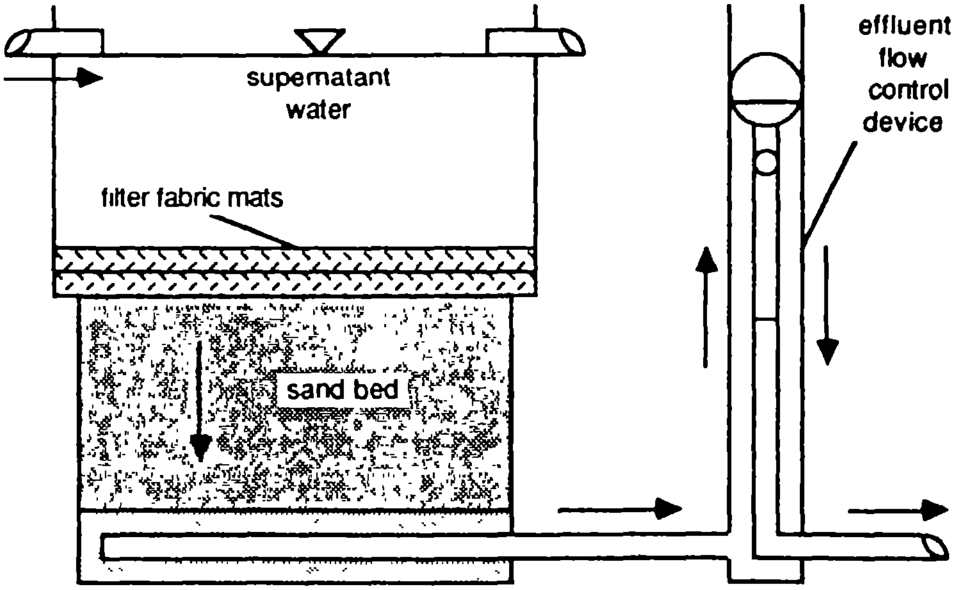


FIGURE 19. Prefabricated (Protected) Slow Sand Filter
Source: Lloyd et al. (1986), pp. 22 & A27

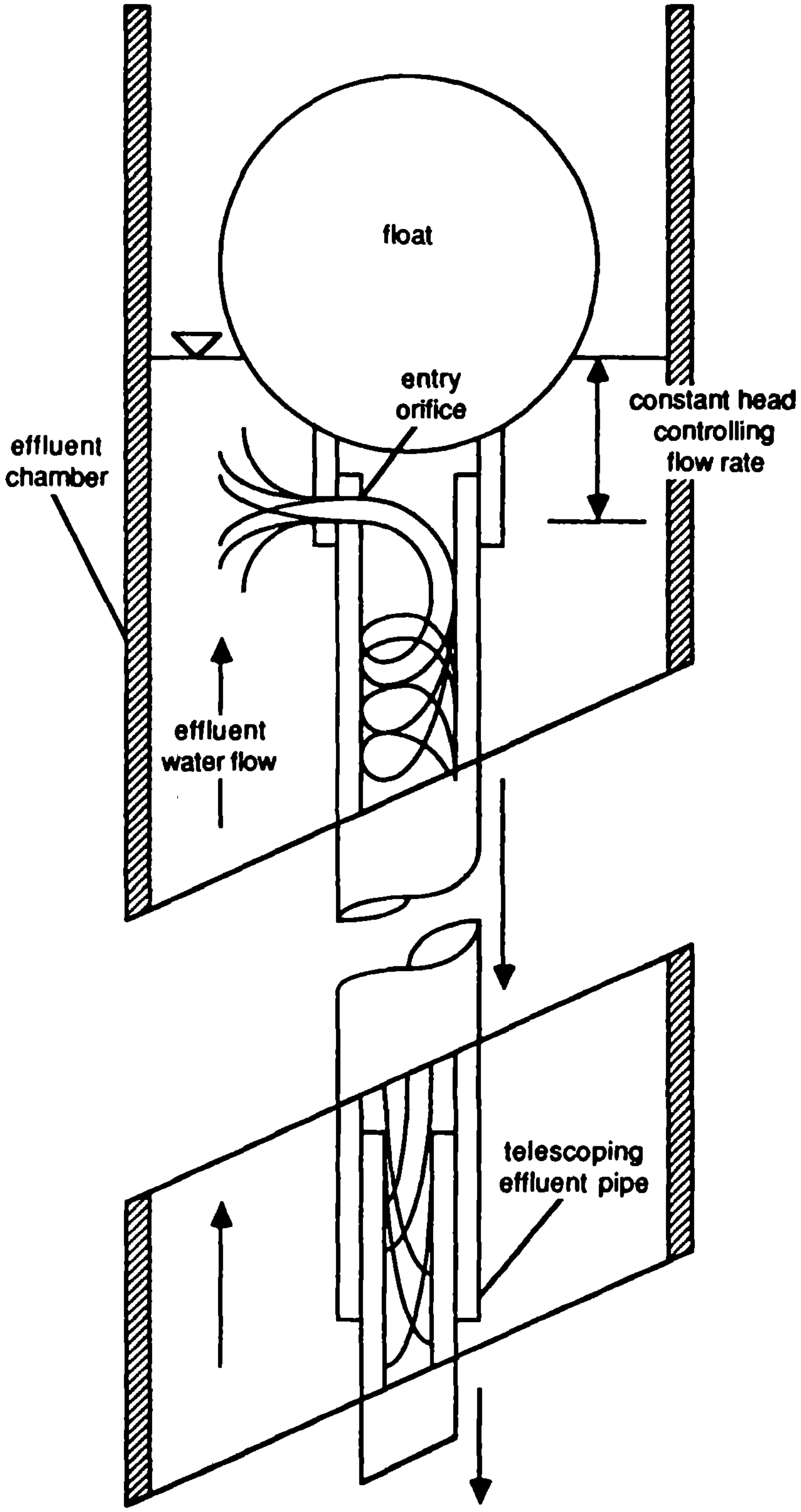


FIGURE 20. Constant Flow Device
Source: Lloyd et al. (1986), pp. A57 & A59

The prefabricated slow sand filters are also equipped with an innovative flow control mechanism, different from those of both the classical and modified slow sand filters. The constant flow device (Figure 20), as it is called, consists of a cylindrical effluent chamber containing a variable-level telescoping effluent pipe. The height of the effluent pipe is controlled by a float which rests at the level of the water in the effluent chamber. The flow rate through the filter controlled by the constant depth (below water) of the orifice which admits water from the effluent chamber to the telescoping effluent pipe. This arrangement ensures that the varying water level in the effluent chamber does not affect the filtration rate.

The water level in the effluent chamber depends on that of the supernatant water in the filter and the head loss through the filter bed (Figure 21). As in the classical slow sand filter, the supernatant water level is maintained a fixed level above the filter bed (about 60 cm in this case). At the beginning of a filter run, the level of water in the effluent chamber -- as well as that of the float -- is at its highest, slightly below that of the supernatant water. As the filter run progresses and the filter bed becomes more clogged, the increased head loss lowers the water level in the effluent chamber. The filter run is over when the float reaches its minimum level (as dictated by the telescoping effluent pipe).

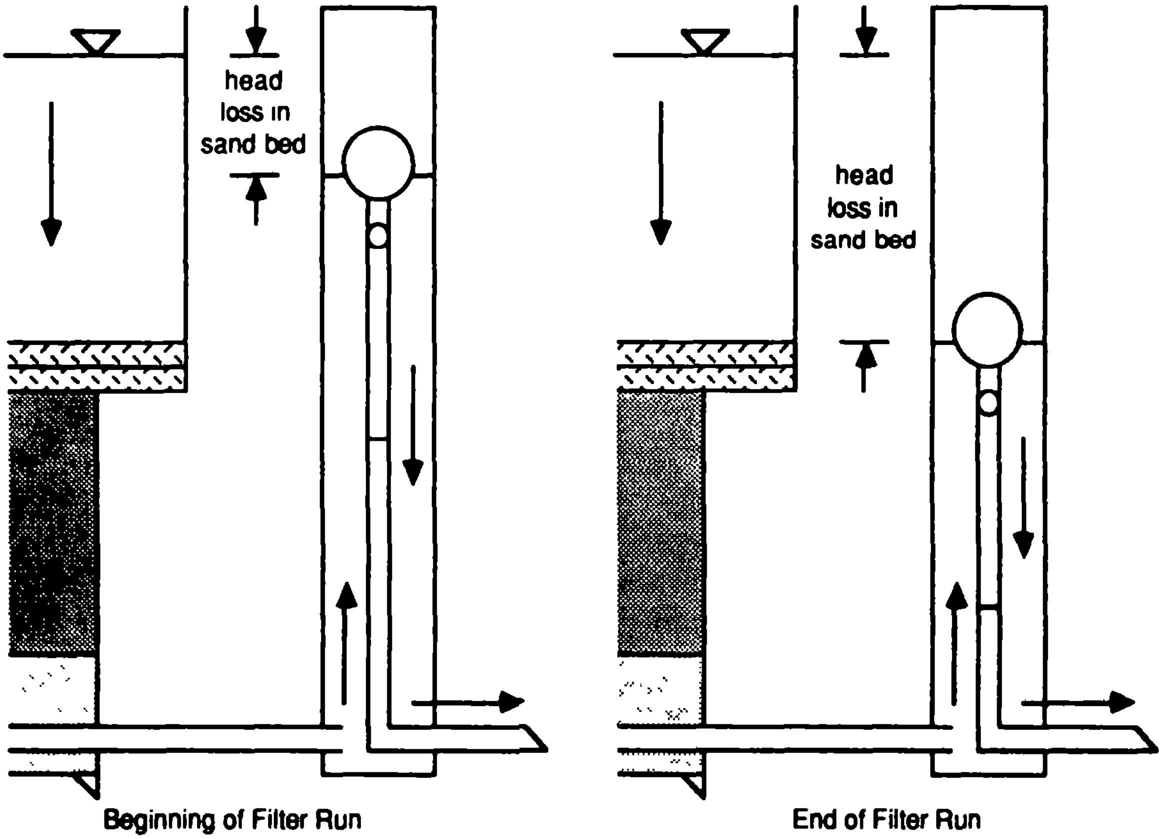


FIGURE 21. Variation of Float and Effluent Water Level Over the Course of a Filter Run in a Prefabricated Slow Sand Filter
Source: Lloyd et al. (1986), p. A57

The distribution system in Azpitia also involves some interesting new components. First of all, to save money, no clear water storage reservoir was included. Instead, the distribution system involves a series of small asbestos cement tanks (Figure 22) placed on the roofs of various houses (12 in all) along the length of the village's main road (see Figure 18). Each tank is filled by gravity flow through the transmission main. Filling is stopped by a float-operated valve when the water level in the tank reaches its maximum level.

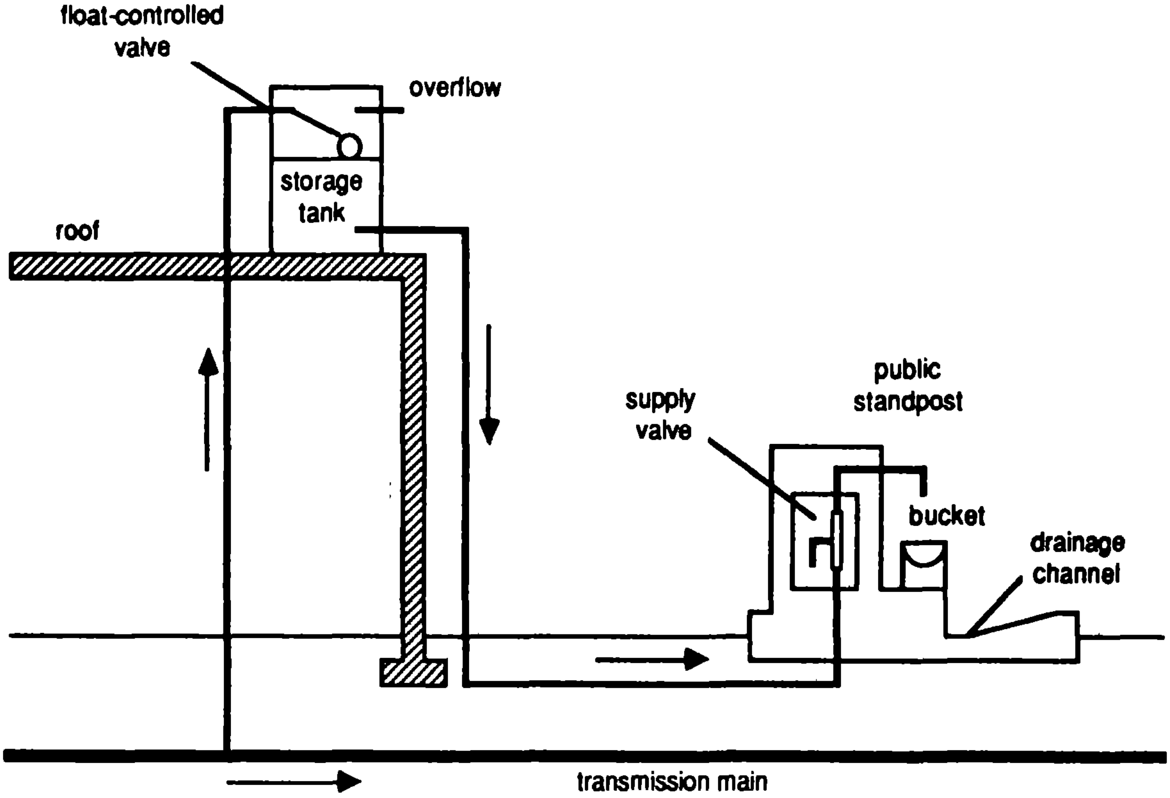


FIGURE 22. Azpitia's Distribution System
Source: Pardón (1987), p.33

The second capital-saving feature of Azpitia's distribution system is the substitution of house connections for 12 public standposts from which water can be collected in buckets. Each standpost is connected to one of the 12 small storage tanks and water flows to the standpipe by gravity when the supply valve is opened. The supply valves are specially-designed for heavy use. Instead of the globe or gate valves conventionally used on water faucets, Azpitia's standpipes are equipped with rotary valves, which are less likely to lift out of their housings. The faucet pipes themselves are made of thick galvanized iron to prevent breaking if buckets are hung from them.

# CONCLUSIONS

While the use of spring water supplies is, realistically, the only possible means of achieving the goal of providing clean water to all rural communities, surface water will continue to play a significant role in Peru as a source of water for those communities who have no ready access to springs. For such communities, slow sand filtration, despite the failure and poor performance of many existing systems, is likely to continue to be the preferred method of water treatment.

In an effort to ensure the continued use of slow sand filtration, Peruvian engineers have made considerable progress in addressing the main technical difficulties hampering its performance (that is, the complexity of the flow control system and clogging under high turbidity). As outlined in this report, this progress involves the development of modified slow sand filters and simplified flow control devices and the adoption of pretreatment by gravel roughing filtration.

Of course, technical difficulties are not the only -- nor are they even the most important -- obstacles to the successful performance of water treatment plants in Peru. While technical improvements, especially in the direction of simplifying operation and maintenance, are essential, it is also critical that these improvements be made available to a greater number of communities than they have in the past. Unfortunately, the implementation of more water supply projects requires a substantial increase in the availability of financial and human resources.

In my estimation, the training of more personnel for work in the field of water supply must be the first priority of the Peruvian government. Personnel problems exist both in the Ministry of Health, where a greater number of engineers and technicians are necessary to carry out water supply projects, and on the village level, where the training of operators must be improved if water supply systems are to be properly run.

Another area which requires improvement is in the coordination of water supply with health and hygiene education. A failure to teach better hygiene practices -- which are particularly poor in the *sierra* -- will seriously mitigate the health benefits of improved water supplies.

Also critical to the improvement of health conditions in rural Peru is the disinfection of water supplies after treatment. As noted in this report, the lack of disinfection is not a technical problem, but one of poor administration and scarce personnel. Hypochlorite dosing mechanisms should be made available to all communities and the hypochlorite distribution system must be reorganized.

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# APPENDIX

## Filter Sand Characteristics

As mentioned in this report, many of Peru's slow sand filters contain improperly-graded sands. The "Manual for the Design of Slow Sand Filtration Plants in Rural Areas" (Pérez & Vargas, 1984) used by DISABAR, recommends that the sand used in slow sand filters meet the following characteristics:

(1) The effective diameter ($d_{10}$) should be between 0.15 and 0.35 mm, although the minimum may be extended to 0.10 mm for very clear raw waters and the maximum may be extended to 0.40 mm for very turbid waters.

(2) The uniformity coefficient ($C_u$) should be below 3.0, with the optimum range being between 1.8 and 2.0.

The are also graphical methods for specifying the size distribution of sand particles, such as that used by DelAqua in its granulometric analysis of sand in Cocharcas's slow sand filters before and after rehabilitation (Figures A1 and A2). The source of data used in plotting this "optimum range" is unknown.

The sand used in Cocharcas before the rehabilitation project carried out in 1985-86 provides an excellent example of the poorly-graded sand used in many of Peru's slow sand filters. As shown in Figure A1, the sand used before rehabilitation did not conform to recommended standards; its effective size (0.32 mm) fell within the accepted range, but its uniformity coefficient (7.8) was much greater than the recommended maximum of 3.0 (DelAqua, 1986). As part of the rehabilitation project, the poorly-graded sand was replaced with sand of much more acceptable characteristics ($d_{10} = 0.21$ mm, $C_u = 3.1$ -- see also Figure A2).

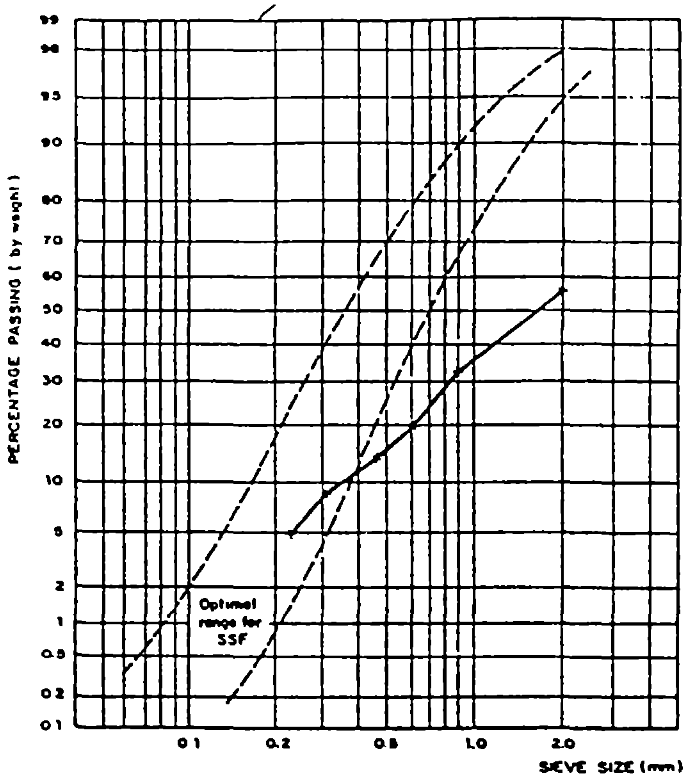

FIGURE A1. Granulometric Analysis of Sand in the Slow Sand Filter Prior to the Rehabilitation of the Treatment Plant in Cocharcas
Source: DelAqua (1986), p.16

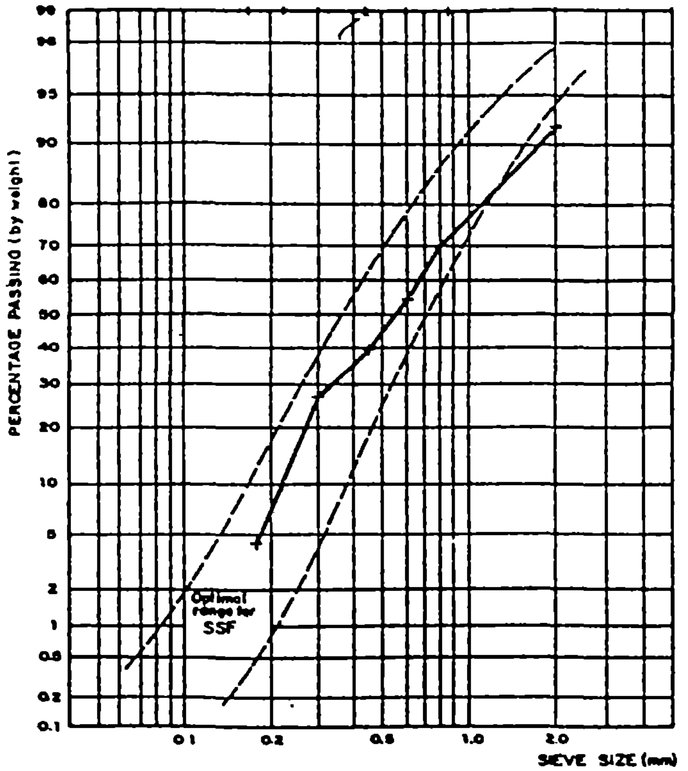

FIGURE A2. Granulometric Analysis of the Sand Used in the Rehabilitation of the Slow Sand Filter of Cocharcas
Source: DelAqua (1986), p.24