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Opportunities for Renewable Energy Technologies in Water Supply in Developing Country Villages

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Introduction

This report provides the National Renewable Energy Laboratory (NREL) with information on village water supply programs in developing countries. The information is intended to help NREL develop renewable energy technologies for water supply and treatment that can be implemented, operated, and maintained by villagers. The report is also useful to manufacturers and suppliers in the renewable energy community in that it describes a methodology for introducing technologies to rural villages in developing countries.

An estimated 1.4 billion people do not have access to safe drinking water. Of these, about 1.1 billion live in rural areas of developing countries. An estimated 10,000 people die each day of waterborne diseases, many of which could be prevented by introducing a proper water supply, adequate sanitation, and improved hygiene. Beyond the toll of human life, these communities suffer a loss in productivity because of illnesses and time women and children spend hauling water (Arthur 1996; WASH 1993).

Many rural villages in developing countries that lack safe drinking water also lack access to electrical power. NREL, as a leader in renewable energy research, is interested in applying its expertise to help solve drinking water problems in these communities. These technologies will significantly expand water supply options.

NREL has contracted to Water for People (WFP) to provide background information on the elements of rural water supply programs in developing countries. WFP is a nonprofit organization that was formed in 1991 by the American Water Works Association (AWWA). Through the support of AWWA's 55,000 members, WFP builds partnerships with, and provides financial and technical support to, local, in-country organizations. During the past 5 years WFP has undertaken more than 130 projects in 25 countries. In the research and writing of this report, WFP was assisted by volunteers for the Water and Sanitation Consultancy Group (WSCG), a nonprofit organization of water professionals in Denver, Colorado. The mission of both WFP and WSCG is to help communities in developing countries obtain and sustain safe drinking water supplies and adequate sanitation.

This report describes the key elements of successful, sustainable village water projects, which include appropriate technology, the creation of local institutions, and a participatory approach during project implementation. Many projects fail soon after construction is complete because the project implementation process failed to meet these criteria. The report focuses on rural villages, which are more likely to lack access to the electrical grid and which, therefore, are potential beneficiaries of renewable energy technologies.

The report covers five topics:

- **Rural Water Supply Problems and Information on Villages.** This section defines the magnitude of the lack of water services in developing countries and the corresponding prevalence of disease. An overview of cultural aspects of village life is provided along with information on employment and income levels.

- **Characteristics of Successful Water Projects.** This section describes the characteristics of successful, sustainable water development by summarizing the 20 lessons revealed in the US Agency for International Development (USAID)-sponsored book *Lessons Learned in Water, Sanitation, and Health: Thirteen Years Experience in Developing Countries*. Key elements described in this section include the formation of local institutions, the involvement of end users, and the incorporation of sanitation and hygiene education (WASH 1993).

- **Village Water Supply Technologies.** This section describes four common types of village water supply systems: (1) gravity flow water supply systems, (2) wells with hand pumps, (3) water systems with motorized pumps, and (4) rainwater catchment. Sample costs for these systems are included.

- **Village Water Treatment Technologies.** This section provides information on water quality concerns, the limited use of water treatment in villages, and types of village water treatment technologies. It also describes conventional water treatment systems and desalination treatment processes.

- **Renewable Energy Considerations.** This section evaluates the application of renewable energy technologies to water system development in rural villages in developing countries.

The report concludes with a summary of information presented in the report and recommendations for further investigation.

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Rural Water Supply Problems and Information on Villages

Rural Water Problems in Developing Countries

Need for Safe Drinking Water

An estimated 1.1 billion people in rural areas do not have access to safe drinking water supplies (WASH 1993). The values in Table 1 compare the access to safe drinking water in several countries and provide values for child mortality rates in these countries. Appendix A provides additional indicators for other countries.

Table 1: 1990 Indicators for Access to Safe Drinking Water and Under Five Mortality Rates for Several Countries (World Bank 1994)

	Access to Safe Drinking Water		
Country	**Urban**	**Rural**	**U5MR***
Haiti	56%	35%	unknown
Bolivia	76%	30%	116
Ethiopia	70%	30%	207
Guinea Bissau	8%	27%	236
Nepal	66%	34%	142
Laos	47%	25%	159
United States	100%	100%	10

* U5MR = Mortality rate for children under 5 years old per 1000 live births.

Incidence of Waterborne Diseases

A 1996 World Bank report cites that of the 17 million people who die each year of infectious diseases, 25% are from waterborne diseases (Arthur 1996). These values equate to 10,000 deaths per day from waterborne diseases. Table 2 lists several common waterborne diseases endemic to many developing countries. Not all are caused by drinking contaminated water. Table 3 shows four categories of water-related infection, of which only the first category is related to drinking contaminated water. Water-washed diseases (Category II) are caused by having insufficient water for proper hygiene. Water-based diseases (Category III) and water-related insect vector diseases (Category IV) are caused, in part, by people washing clothes and bathing near contaminated surface waters.

Table 2: Incidence and Effects of Selected Diseases in Developing Countries (WASH 1993)

Disease	Incidence*	Estimated Deaths/Year
Diarrhea	875 million	4,600,000
Acariasis	900 million	20,000
Guinea worm	4 million	**
Schistosomiasis	200 million	**
Trachoma	500 million	***

* Estimated cases per year
** Effect is usually debilitation rather than death
*** Major disability is blindness

Table 3: A Classification of Water-Related Diseases
(Waterlines 1988)

Category	Examples	Relevant Water Improvements
I Waterborne infections		
a. Bacterial	Typhoid, cholera	Microbiological sterility
b. Nonbacterial	Infectious hepatitis, ascariasis	Microbiological improvement
II Water-washed infections		
a. Skin and eyes	Scabies, trachoma	Greater volume available
b. Diarrheal diseases	Bacillary dysentery	Greater volume available
III Water-based infections		
a. Penetrating skin	Schistosomiasis	Protection of user
b. Ingested in water	Guinea worm	Protection of surce from fecal contamination
IV Infections with water-related insect vectors		
a. Biting near water	Sleeping sickness	Water piped from source
b. Breading in water	Yellow fever	Water piped to site of use
V Infections primarily of defective sanitation	Hookworm	Sanitary fecal disposal

Water System Sustainability Problems

Many water systems are not maintained and fail soon after construction. In 1990, the Collaborative Council Working Group on Operation and Maintenance issued the following statement to draw attention to the need for a new philosophy for water system operations and maintenance: "The operation and maintenance of water supplies and sanitation in developing countries is badly neglected, so much so that many of the schemes have fallen into disrepair and no longer provide the services for which they were constructed. Because of this, the actual coverage levels of adequate water and sanitation in developing countries is even lower than statistics would suggest." The complete statement by the Working Group is provided in Appendix B.

Some reports state that 40% to 60% of village wells with hand pumps in African countries are not functioning (Ittisa 1991). Another report cites a 60% failure rate for village water systems in Malawi (Save the Children 1993). There is a high failure rate for water systems in Africa, Central America, South America, and Asia. This poor record of water system sustainability can be blamed, in part, on the emphasis that implementing agencies have placed on construction instead of on training villagers and building local institutions. Another problem is that villagers view water as a free commodity and do not recognize the need to pay for the water system operations and maintenance. When water systems fail, local people return to hauling water from distant, traditional sources of questionable quality. These issues of sustainability apply equally to conventional and renewable energy sources.

The section, Characteristics of Successful Water Projects, considers aspects that affect water and energy system sustainability.

Village Cultural and Socioeconomic Factors

An estimated three billion people in rural areas of developing countries live in and around an estimated two million villages (WASH 1993; Critchfield 1995). Nearly one-third of these villages are in China, and another third in South Asia (primarily India, Pakistan, and Bangladesh). In Indonesia there are some 60,000 villages. In Ethiopia, by contrast, there may be no more than 10,000. There are no thresholds that define minimum and maximum sizes of villages; however, most village populations worldwide range from 50 to 3,000 persons.

Cultural Patterns

When considering village-based water improvement projects, the project implementers must take into account cultural patterns for transmitting information. Communications through extended family and kin networks often take precedence over written and media sources. Village councils are key to village decision-making, and local government officials must also be consulted. In villages, there are often internal political tensions, and formal communication networks may not function smoothly. Project-oriented discussions should take place in community meetings, but traditional decision-making hierarchies may prevail.

Poverty Reduction

Measurable poverty reduction is deemed essential to promote the development of sustainable infrastructure such as water supply systems. Income levels of local people must increase so they can afford to operate and maintain water services. In the 1970s and 1980s the greatest economic gains occurred in southeast Asia and the smallest in Africa. Where the poor's most abundant asset, labor, has been used (as in Indonesia), economic development has been relatively successful. Where economic growth has been promoted but local economic opportunities for villagers have not materialized (as in Nigeria), there has been no development progress (World Bank 1990).

Services

Policies that promote only national growth have not been highly successful. Educational opportunities, including those related to technology and field training for villagers, must also be promoted. Social and support services must be in place with primary health care, nutrition, and family planning being key services (World Bank 1990).

Village Economies

Local economies tend to be highly labor-dependent and labor-intensive. Agricultural and market activities predominate. The informal sector has an active role in the economy. Microentrepreneurs and unregistered street vendors play vital roles, but their economic effects are difficult to measure.

Agricultural activity is performed by a small number of large landholders, a large number of smallholders, and numerous tenant farmers, sharecroppers, and migrant laborers. On the village level, subsistence activity predominates over cash crop activity. Land rights often are tenuous or in flux (see, e.g., Feder and Noronha 1987). Land redistribution plans do not yield short-term gains for most villagers (World Bank 1990).

More than 80% of all developing nations rely substantially on migrant labor. Seasonal migration patterns of laborers substantially affect agricultural productivity and resource availability. Such laborers in the Horn of Africa supplement their incomes in this manner; those in Southeast Asia use the cash derived as their primary source of income.

Representative village household incomes in countries such as Guatemala, Bolivia, Ethiopia, Malawi, and Vietnam range from $100 to $300 per year. This income comes from the sale of their crops and sometimes short-term employment as day laborers. The daily pay for day laborers in these countries ranges from $1.00 to $4.00 per day. Money earned by villagers is used to buy such staples as kerosene for lamps, salt and oil for cooking, and clothing.

Roles of Women in Water Supply

Women, as household managers, are responsible to fetch water for food preparation, washing, and bathing. In rural Africa, it is not uncommon for a woman to walk 6 to 8 kilometers with a 25-liter pail of water on her head or back (Curtis 1989). In order to provide a 10-person household with sufficient water for adequate hygiene (45 liters/day), women would have to make 18 trips to the water source per day. Hauling water consumes huge amounts of time that could be used for other activities.

Male development workers often have trouble relating to village women and therefore do not include women in project decision-making processes (Rogers 1989). Women, being responsible for hauling water, will have opinions regarding new water points and be active promoters of water and sanitation improvements. Hygiene education is also best directed to women, because women are responsible for water handling and storage (Elmendorf and Iseley1989). Women will advocate water system maintenance when they recognize the connection between the health of their families and the quality of their drinking water.

Methodology for Studying Villages before Water Projects Are Begun

Before beginning a village water, sanitation, or health project, the implementing agency should perform a baseline survey of the village to determine the need for the project and collect basic information on the village. Often these surveys are referred to as Rapid Rural Appraisals (RRAs) or Rapid Needs Assessments (RNAs), and are used to help organizations develop program designs for multiple village water projects in an area. A second type of survey is the Participatory Rural Appraisal (PRA), which focuses on facilitating workshops in which all members of the community define their greatest problems and needs. PRAs are more time-intensive than RNAs, but extensive community participation in PRAs helps the community prepare to take responsibility for implementing the project. More information on the type of data collected during baseline surveys is included in Appendix C.

A third type of survey is the Knowledge, Attitude, Belief, and Practices (KABP) study, which often is conducted by social scientists and consists of extensive interviews with people in the community. Through KABP studies, information is gathered on topics that include hygiene and sanitation practices, beliefs concerning the source of diseases, attitudes regarding the need for village development, and information on village leadership and decision-making processes. A KABP study allows educational elements of the project to be culturally sensitive. In addition, a second KABP study at the end of the project helps evaluate the success of the educational components of the project.

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Characteristics of Successful Water Projects

As noted in the previous section, there is a high failure rate for rural water systems in developing countries. The high failure rate can be blamed, in part, on the emphasis that has been placed on construction instead of training local people and strengthening local institutions. Water development agencies agree that water projects need to focus on involving local people in the implementation process. In this process water users choose the type of water system that suits their needs and the local government coordinates water sector activities. When local people are involved in project decision-making, they accept responsibility for the success of the project.

The importance of community involvement and institutional development are described in numerous publications (Colin and Ball 1991; Kerr 1989; Kerr 1990; Chaudan 1983). In the document *Lessons Learned in Water, Sanitation and Health,* the staff of the Water and Sanitation for Health (WASH) Project summarizes its 13 years of experience with USAID-funded water and sanitation projects. As part of the USAID emphasis on project evaluation, this 1993 text (first produced in 1990) defines 20 lessons that reveal the characteristics of successful water projects. The following text summarizes this document and provides additional insight into how these lessons pertain to the renewable energy field.

Technical Assistance

"Technical assistance is most successful when it helps people learn to do things for themselves in the long run."

Lesson 1: *"Effective technical assistance focuses on* ***building local institutions*** *and transferring sustainable skills."*

This lesson points out that the process of technical assistance is as important as the actual products of the technical assistance. Stated another way, in order for the country to manage water systems and renewable energy systems over the long term, the project must promote the development of institutions and technical and managerial skills within the country.

Lesson 2: *"Technical assistance in water supply and sanitation requires an* ***interdisciplinary approach****, not a narrow, specialized one."*

Successful water and renewable energy projects include assistance in management, finance, policy planning, and training, and are tailored to local cultural circumstances. There is a special danger that the renewable energy industry could consider a water supply application without obtaining expertise in water and health areas.

Lesson 3: *"A* ***participatory approach****—facilitation, not dictation—maximizes the chance that programs and projects will be sustained."*

When local people are involved in the project decision-making process, they will take responsibility for the success of the project. Participants in the planning process must include local villagers and government officials.

Lesson 4: *"Technical assistance provided through* ***collaboration*** *of multilateral and bilateral agencies and AID-funded projects makes maximum use of scarce resources."*

Through enhanced communications between government agencies, nongovernment organizations (NGOs), and donors, cooperation can replace competition for scarce funds. These collaborative efforts can create policies such as requirements for village contributions and the need to include hygiene education and sanitation in projects. For renewable energy water projects, this implies a need for greater cooperation between the Department of Energy, NREL, and other donor groups and implementing agencies.

Lesson 5: *"An **active information service** can expand the reach, as well as the visibility and credibility, of technical assistance."*

The experiences gained in implementing projects, both successful and unsuccessful, must be communicated to implementers of future water and renewable energy projects. The dissemination of information via written materials is more cost effective than seminars or reconnaissance visits by experts. There is good information in the United States on the design of photovoltaic (PV) and wind pumping systems, but it is not available to designers in developing countries.

Shared Responsibility

"Sustainable development is more likely to occur if each of the key participants recognizes and assumes its appropriate role and shoulders its share of the responsibility."

Lesson 6: *"The **role of the government** is to assume primary responsibility for sector management, including planning, donor coordination, policy reform, regulation and institutional and financial aspects of development."*

Developing country governments must take the lead in developing the water and renewable energy sector in a country by establishing clear national goals, plans, policies, and institutions. Such efforts by the government result in documented project implementation standards for use by NGOs. Renewable energy is most successful in developing countries where the national governments have taken lead roles.

Lesson 7: *"The **donor's role** is to provide coordinated support to governments in designing or carrying out its national plans."*

If water and renewable energy programs are to be sustainable, they must reflect the government's priorities, not those of the donors. Donors should not stipulate provisions to their assistance, but should collaborate in the planning process with the government.

Lesson 8: *"**Nongovernment organizations** are able to operate effectively just where donors may find it difficult to do so—on the local community level and in politicized situations."*

WFP typically supports the activities of international NGOs (i.e., CARE) or indigenous NGOs. The strengths of NGOs are their commitment to project beneficiaries, neutrality in local politics, ability to mobilize and adapt quickly, a reliance on indigenous staff, cost effectiveness, and (in the case of international NGOs) the ability to obtain financing. Typical weaknesses of some NGOs include a lack of engineers and administrators (because of funds), a lack of coordination with other NGOs, and a short-term commitment to the program area. NGOs that have a long-term presence in an area are better able to coordinate their activities with other local institutions, incorporate lessons learned from previous projects, and are more accountable for the quality of their work.

In the renewable energy field, there is not the same network of NGOs as in the water development field. NGO participation in the renewable energy field can be fostered through education programs directed at NGOs by organizations such as NREL.

Lesson 9: *"The participation of users in water supply and sanitation systems, whether in rural or urban or peri-urban communities, is critical to long-term sustainability."*

The responsibility to operate and maintain a water system rests with the benefiting community because developing country governments do not have the financial capability to maintain thousands of rural water systems. Before the project is begun, the community must first decide that an improved water service is something it is willing to support financially. In addition, the community must decide the level of water service it needs. Community involvement develops a sense of local ownership in the system and incorporates local knowledge of water sources, community history, local building techniques and local habits toward water use and hygiene. To facilitate community involvement in the project, the implementing agency (i.e., NGO) helps the community start a water committee. After the project is complete, the water committee is responsible to operate, maintain, and administer the system, and collect water user fees.

Meaningful local participation means including everyone in the community, not only the most visible leaders. Efforts need to be made to include women in project decision-making, as they are the primary water users. Women are often responsible for fetching water, so their ideas about the locations of community water points and clothes-washing areas must be incorporated. They are also responsible for the use of water and the care of children, so they should be trained to educate other women about proper water storage, sanitation, and hygiene.

Communities should contribute their ideas, materials, labor, and money to the project. Typical in-kind contributions of village labor and materials should be equal about 25 % of the project cost. To promote the recognition that an improved water service is not free, many NGOs ask communities to contribute 5% to 10 % of the project cost in cash, which can be used for construction and to start a maintenance fund.

Similarly, the participation of the beneficiaries is important to renewable energy projects. Project planning and implementation must consider provisions to ensure the sustainability of the renewable energy technology.

Lesson 10: *"The private sector's role in providing water supply and sanitation services can be expanded if governments can create a supportive institutional, financial and legal environment for private sector participation."*

In rural water and renewable energy projects, the role of the private sector is to manufacture and distribute the materials used for construction and maintenance. These materials should be readily available and affordable to communities. With regard to the promotion of renewable energy technologies, the development of the private sector should parallel the implementation of village renewable energy projects.

Program Strategies

"The most effective water and sanitation strategies are those that concentrate on eliminating the constraints that prevent facilities from yielding their expected health benefits."

Lesson 11: *"The success of individual water supply and sanitation projects depends on **strong sectoral policies and institutional practices.**"*

Government policies that include the promotion of economic growth, education, decentralization, and political reform will increase water project success rate. Poverty and inefficient government are detrimental to the implementation of both water and renewable energy services.

Lesson 12: *"**Sanitation** should be accorded the same priority as water supply."*

Sanitation in rural communities usually means latrine construction. More people in the world lack adequate sanitation than lack access to safe drinking water. In order for the health benefits of a safe drinking water supply to be realized, sanitation and hygiene education must be part of the project.

Lesson 13: *"Improvements in **hygiene-related behavior** are an indispensable measure of success for water and sanitation."*

Hygiene education is an important component of every successful water project in that it promotes proper water storage, hygienic behavior such as hand washing, and latrine construction. In addition, hygiene education helps people understand the importance of maintaining their water systems and latrines.

Lesson 14: *"**National governments** must take specific policy steps to ensure that **communities** have the capacity, and are empowered to manage water and sanitation activities."*

An important reason for the failure of many rural water systems is that government agencies and NGOs do not support communities' efforts to administer and maintain their water systems. Village water committees would benefit from regular training in the administrative and technical aspects of operating their water systems. Villages that employ renewable energy technologies would similarly benefit from continued support after the installation phase of the project is complete. Without such support, the collection of water fees or electrical fees by the community committee may be a short-lived idea. In Honduras, there are "circuit riders" whose sole task is to regularly visit communities and provide assistance with their water system.

Lesson 15: *"A **participatory approach** to planning helps to forge necessary linkages in and outside the sector and to ensure cooperation in implementation."*

Water project planning should include diverse groups that comprise government agencies involved with water, health, and natural resources. Together, these entities should develop short- and long-term goals and plans. Their participation is important in water and renewable energy projects to foster local responsibility for maintaining the completed projects.

Lesson 16: *"The command and control model that usually governs **water and sanitation regulation** in developed countries is not generally appropriate for developing countries."*

Protecting the quality of water sources should be promoted through education and incentives rather than through regulations.

Long-Term Sustainability

"The basic measure for success of both the national system for development and community management systems it creates is sustainability—the ability to perform effectively and indefinitely after donor assistance has been terminated."

Lesson 17: *"Successful **institutional and human resources development** projects are comprehensive, systematic, participatory and based on long-term planning."*

To develop the water and renewable energy sectors, there needs to be an emphasis on identifying educational needs and providing training.

Lesson 18: *"Full consideration of **appropriate engineering design** and application is essential to system sustainability."*

The technology used in a project must pass several socioeconomic tests. Do local people conceptually understand the technology? Are spare parts available to maintain the technology? Is the technology affordable in terms of maintenance and replacement? Is the technology attractive to the local people? For example, pit latrines may be unattractive because of their smell and will not be used.

The technologies of choice also depends on the availability of local expertise and materials. Members of the local community are best able to suggest the type of technology for their water system based on their own experiences. The technology also depends on national design standards such as standards for hand pumps or pipes, or it might be based on the types of materials that can be purchased in the country.

Lesson 19: *"Making **operation and maintenance** plans before facilities are constructed and in place helps ensure that sustainable technologies are selected."*

During the project planning process, the community and the implementing agency need to discuss operations and maintenance. What type of operation and maintenance will be needed? Can community members be trained to operate and maintain the water system or renewable energy system? What will be the cost of operating and maintaining the system? How much is the community willing to pay? Is outside expertise needed for operations and maintenance? If so, who will provide this expertise and for what cost?

Lesson 20: *"To be sustainable, the water supply and sanitation sector must rely on **an appropriate mix of** donor, national government, and community financial resources."*

Development efforts should not promote dependency on foreign aid or foreign technical assistance. Users must be able to pay for ongoing operation and maintenance and, increasingly, a portion of the initial construction cost.

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Village Water Supply Technologies

This section begins by presenting values for water consumption that are used for water system design. It then defines four categories of water systems that are commonly used in developing country villages: (a) gravity flow water systems, (b) wells with hand pumps, (c) systems with motorized pumps, and (d) rain water catchment. The section concludes by presenting representative costs for each category.

Water Consumption

Water demand in developing countries varies with climate, social habit, ease of access, and quality of water. For example, in the frigid Bolivian altiplano, water consumption is less than in the more temperate areas of Bolivia. Studies have demonstrated a relationship between the quantity of water consumed and the distance people have to walk to fetch it (WaterAid 1993). This relationship is important in that improved hygienic practices require people to use more water.

The nomenclature for water consumption is expressed as liters per capita per day (lpcpd). The World Health Organization's (WHO) recommendation for consumption is 45 lpcpd, although local governments may have their own standards (Jordan 1980). Table 4 presents typical flows used to design a village drinking water system. The determination of water system design flows must tabulate the consumption of current and future water users. Many water systems are designed to provide water for a 20-year design period. In individual countries there is often published information on estimated population growth rates, and villagers can provide insight to future population increases.

Table 4: Water Consumption

	(lpcpd)
Community or household tapstands [1]	45
Schools, day [1]	10
Schools, boarding [1]	65
Hospitals and health posts [1]	500 per bed
Government offices [2]	30
Livestock [2]	
Horses	35
Cattle	40
Pigs	15
Sheep	12.5
100 Chickens	15

1 Jordan 1980
2 WaterAid 1993

Gravity Flow Water Systems

A gravity water system relies on a water source that is located at a higher elevation than the community. The major components of a gravity water system are a spring or stream intake, a reservoir tank, distribution pipelines, break pressure tanks, and communal or household tapstands. Break pressure tanks eliminate excessive water pressure that would otherwise rupture the pipeline. Figure 1 shows a schematic of a gravity water system. Table 5 summarizes the physical components of a gravity water system. Besides the physical components, water supply systems also have nonphysical components such as the institutions needed to operate and maintain the systems.

When there is an adequate source of water above the community, gravity water systems are often preferred because they can bring larger amounts of water close to the users' homes. One problem inherent to gravity water systems is that water shortages occur when broken faucets are not replaced and local people construct new branch lines and faucets. The village-level remedy to these water shortages is to release water from the reservoir tank for only a couple of hours in the morning and evening.

Gravity flow water systems are the primary systems in rural countries such as Guatemala, Honduras, Nicaragua, Ecuador, Bolivia, and Nepal. The cost of representative gravity water systems is compared to other types of village water systems in Household Rain Catchment Systems. The best text on gravity flow water systems is the *Handbook of Gravity Flow Water Systems for Small Communities* (Jordan 1980).

Figure 1: Schematic of a Gravity Flow Water System
(Jordan 1980)

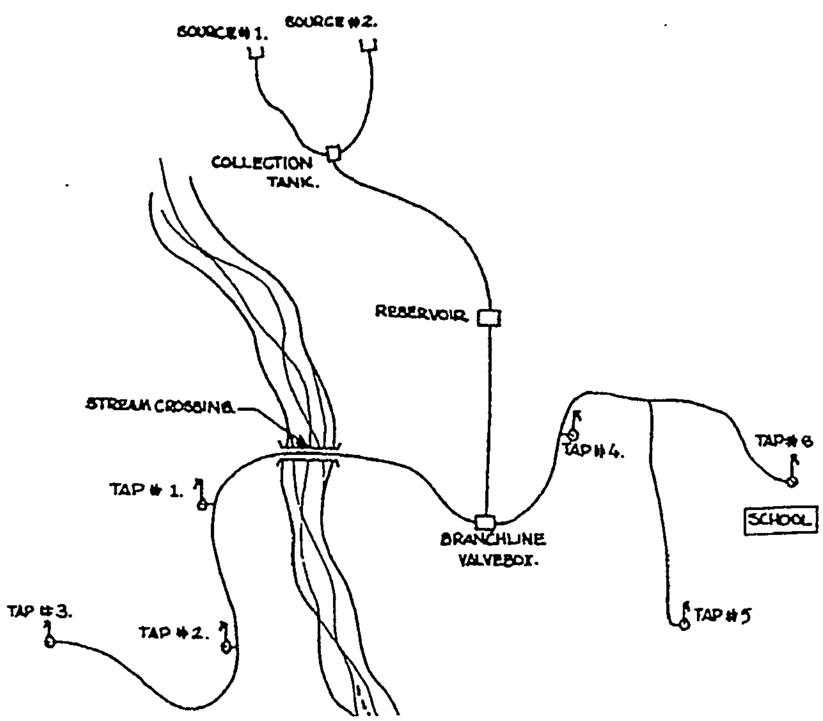


Table 5: Components of Gravity Flow Water Systems

Category	Component Type	Description
Water Sources	Springs	A spring located above the community provides a high-quality water source. Potential problem: insufficient flow during dry seasons.
	Surface Water Sources (i.e. streams and lakes)	A surface water source above the community can be created by a dam or diversion structure. Potential problem: contamination from upstream inhabitants and agriculture.
	Surface Rainwater Catchment	Rainfall onto a hillside with low permeability will allow runoff to be collected in a berm at the base of the hill. Potential problems: contamination by people and animals and large storage requirements if rainfall is seasonal.
Transport	Plastic Pipe	Commonly ½- to 2- inch PVC or polyethylene pipe for long stretches. Potential problems: exposed plastic pipe deteriorates in the sun or can be damaged by vandals or animals.
	Metal Pipe	Commonly galvanized iron (g.i.) pipe for exposed pipeline stretches and pipes embedded in masonry. Potential problem: g.i. pipe is expensive.
Storage	Ground Surface Tanks	Tanks provide diurnal storage of water. Commonly concrete, with a capacity of 1 m^3 to 50 m^3.
	Tower Mounted Elevated Tanks	Used when a ground surface tank would have to be located too far from the community.
Water Points	Household Tapstands	Tapstand with faucets at individual homes. Potential problem: excessive water use is difficult to control.
	Community Tapstands	Tapstands serve 5 to 15 homes. Potential problem: tapstand repair requires social cohesiveness.
Other Appurtenances	Break Pressure Tank	A small tank with a float valve reduces pressures that would otherwise rupture the pipeline. Potential problems: float valves frequently fail and communities cannot afford to replace them.
	Valve Boxes	Control valves, air release valves, etc. Potential problem: difficulty in making valve boxes accessible only to authorized personnel.

Wells with Hand Pumps

Hand pumps can be placed on hand-dug or drilled wells. When conditions allow, hand-dug wells are preferable because they are less expensive, involve the community in project implementation, are easily deepened, and can still provide water if the hand pump fails. Hand-dug wells usually reach a depth of 25 meters. When an aquifer cannot be reached by hand digging, a drill rig is necessary.

Several varieties of hand pumps can pump water from a depth of up to 100 meters. Many well programs are designed to provide one well and hand pump per 250 to 500 inhabitants. For such high-use applications, durable hand pumps have been developed. The governments of many developing countries specify a particular hand pump to ensure that spare parts are available and that government technicians can help communities maintain their hand pumps. A description of the components of hand pump water supplies is presented in Table 6. Costs for village wells with hand pumps are discussed in Discussion of Costs.

There is a high failure rate for village hand pumps in Africa (Ittissa 1991). As a result, many experts such as Peter Morgan in Zimbabwe advocate the installation of wells for a single household or small groups of households (Morgan 1996). Household wells can use windlasses with buckets and thus eliminate the need for expensive hand pumps. During droughts, their depth can be readily increased. From a public health point of view, household wells also promote better hygiene as the convenience of having water nearby promotes increased consumption. Figure 2 shows a hand-dug well with a windlass.

In some places overpumping is depleting aquifers. Consequently, it may be necessary to develop surface water supplies that require water treatment. However, in most developing country villages overpumping is not a problem, as water demands are low and shallow aquifers are seasonally recharged.

Figure 2: Well with Windlass (Morgan 1991)

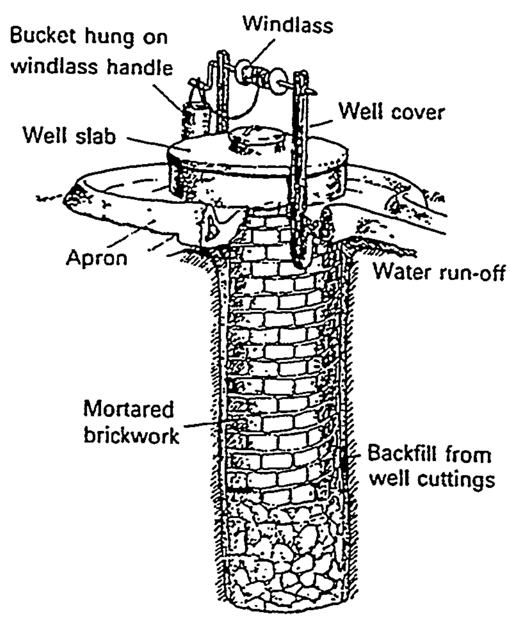


Table 6: Components of Wells with Hand Pumps

Category	Component Type	Description
Water sources	Hand-dug wells	Hand-dug wells are typically 1- to 2-meter diameter pits dug to a depth of 25 meters. Wells are lined with bricks, rocks, or concrete rings either during or after excavation. Potential problem: communities can spend months digging a dry hole (Watt 1978).
	Hand-drilled wells	Hand augers can be used when the aquifer is shallow and rocks are not present. Potential problems: well cannot be deepened during drought and if the pump breaks, water is unavailable (Morgan 1990).
	Machine-drilled wells	Various types of drill rigs can install wells in formations to required depths. Potential problems: lack of community involvement, excessive cost, many areas are inaccessible to drill rig, and if the pump breaks, water is unavailable.
Types of hand Pumps (Waterlines July 1993)	Windlass, rope, and bucket	Manually turning the windlass winds the rope around a spool and pulls the bucket from the well. Potential problems: not recommended for high use and potential for contamination (Morgan 1990).
	Rope and washer pumps (Cost: $120)	By turning a windlass, a loop of rope with rubber washers drags water up a pipe to the surface (Alberts 1993).
	Suction pumps	Above ground plunger in the pump allows water lifting from a depth of 7 meters.
	Direct-action pumps (Cost: $500)	Like suction but plunger is at base of pump, allowing efficient water lifting from a depth of 15 meters.
	Positive displacement pumps (Cost: $500 to $1,000)	Most common village pump contains a piston discharge valve and foot valve. Recommended maximum pumping depth is 100 meters.
	Progressive cavity pumps	A twisting rotor creates a progressive cavity that screws water to the surface.
	Diaphragm pumps	The expansion and contraction of a water-filled cylinder forces water to the surface.
Transport/ storage	Household storage	Water is transported and stored in open pails or (more preferably) in containers with faucet or spout.
Water points	Household wells	Wells with windlasses can provide water to fewer than five households.
	Community wells	Many hand pump programs are designed to provide one well to 250 to 500 inhabitants.

Water Systems Using Motorized Pumps

In some developing country communities, village water systems contain a motorized well pump that pumps water from a water source located below the village to a storage tank that is located higher than the village. Water sources can be wells or streams. The storage tank can be constructed on a nearby hill or can be elevated on pillars. From the elevated storage tank, water flows by gravity to communal or household tapstands. Pumps can be manually operated or float switches in the reservoir tank can be installed to automatically turn on the pump when the tank is empty.

Pumps used in such applications are usually submersible or surface mounted centrifugal pumps. Water systems that use motorized pumps to lift water are usually installed only where there is access to grid electricity. There are diesel applications, but communities can have difficulty affording the $2.00 to $3.00 per day cost of diesel. The renewable energy systems described in Renewable Energy Considerations principally compete with diesel pumps. The thousands of PV and wind- powered water supply systems (described in Renewable Energy Considerations) have often been installed to eliminate the cost of diesel for remote users. Regardless of the energy source, communities often are not able to afford a new pump when the first pump wears out.

Table 7 summarizes the components of village water systems with motorized pumps.

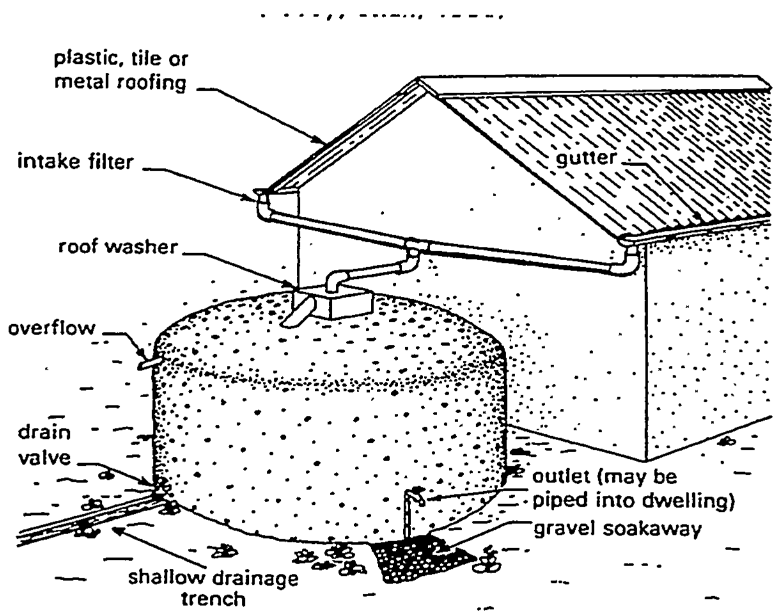
Table 7: Components of Water Systems with Motorized Pumps

Category	Component Type	Description
Water Sources	Hand-Dug Wells, Hand-Drilled Wells, and Machine-Drilled Wells	Same as for Table 3—Components of Wells with Hand Pumps.
	Infiltration Galleries	Porous chamber into which water from nearby surface water seeps. Infiltration galleries are discussed in Village Water Treatment Technologies pertaining to water treatment.
Types of Pumps	Centrifugal Pumps Mounted at Ground Level	Typically single phase or diesel motor powered ½ hp to 3 hp pumps. Renewable energy pumps are often direct current.
	Submersible Pumps	Same as for centrifugal pumps.
Transport/Storage/ Water Points	Household Storage	Same as Table 5—Components of Gravity Flow Water Systems.

Household Rain Catchment Systems

Household rain catchment systems consist of gutters on a home that direct water to a storage tank next to the house. Some require the installation of galvanized roofing because people object to the taste of water coming off a thatched roof. Household rainwater catchment systems are chosen when rainfall is adequate or wells or gravity water systems are technically infeasible or prohibitively expensive.

Figure 3: Rooftop Rainwater Catchment System
(Pacey et al. 1986)



Discussion of Costs

Table 8 presents the costs of several recent village water projects. WFP received funding requests for all these projects, but did not sponsor all of them. The presented costs include all expenses associated with implementing the projects, except for in-kind contributions from the benefiting community. Therefore, these costs include project components such as transportation, salaries, community development, and hygiene education. The Nicaraguan organization Agua para la Vida estimates the cost of a gravity water supply system to be more than double the cost of materials. In Ghana, WaterAid estimates the cost of a hand-dug well with windlass to be $2,200. Of this cost, $800 is for construction materials and equipment, and $1,400 is for hygiene education, transportation, and salaries.

Cost per Beneficiary

The cost of village water systems is typically expressed as the implementation cost per beneficiary. For gravity water systems these values range from $10 to $100 per beneficiary. Wells with hand pumps are usually less expensive than gravity water systems, with typical costs ranging from $3 to $25 per beneficiary. Similarly, water systems with motorized pumps and rainwater catchment systems range from $10 to $100 per beneficiary. The shortcoming of using cost per beneficiary as an indicator of project efficiency is that some of the neediest communities are far from water sources and require more expensive solutions such as longer pipelines or deeper wells.

Table 8: Sample Costs for Typical Village Water Systems

Type of Water System	Location	Number of Beneficiaries	Cost*	Cost per Cubic Meter**	Comments
Gravity flow system	Wayasama, Nicaragua	570	$23,000 ***	$0.39	Communal tapstands
	Vilomilla, Bolivia	700	$25,000	$0.36	Communal tapstands
	Corralcay, Guatemala	146	$10,000 ***	$0.56	Communal tapstands
Wells with hand pumps	San Estaban, Nicaragua	234	$800	$0.06	Hand-dug well with rope pump
	Upper East Region, Ghana	250	$2,300 (3)	$0.09	Hand-dug well with windlass
	Zimbabwe Family Well	10	$100	$0.09	Hand-dug well with windlass
	Sapone, Bukina Faso	500	$1,700	$0.06	Hand-dug well with hand pump
Water systems with motorized pumps	El Salado, Ecuador	55	$3,700	$0.59	Hand-dug well. Electrical connection donated by the electrical utility.
	Clementina, Ecuador	360	$5,500	$0.29	Same as above
Rainwater catchment	Gatune, Kenya	32	$1,193	$0.26	4 tanks, each 5,000 liters
	San Lorenzo, Ecuador	community house	$900	n.a.	4,000-liter tank

* Cost includes materials, skilled labor, administration, and transportation, but neglects the village's contribution of unskilled labor.

** Based on a 10-year project life and a water consumption of 45 liters per day. Operations and maintenance costs (water user fees) for gravity flow systems, wells with hand pumps, water systems with motorized pumps, and rainwater systems are assumed to be $0.20, $0.05, $0.25, and $0.05 per person per month, respectively. Assuming six people per household, these costs equate to monthly household water user fees of $1.20, $0.30, $1.50, and $0.30.

*** This project cost includes the hygiene education component.

Table 8 also compares the cost per cubic meter of water for several village water systems based on a 10-year system life and 45 lpcpd consumption. The water cost for the water systems in Ecuador with motorized pumps was low because these communities are very compact and only short pipelines were needed. The water cost for the Kenyan rainwater catchment system was high because of the large storage volume required for water storage through a long dry season. Rainwater catchment systems are less expensive where rainfall patterns do not require large storage tanks.

Community Contributions to Construction

Generally, communities are asked to contribute locally available materials (sand, wood, and gravel) and unskilled labor to a project. Local people excavate wells, dig trenches for pipelines, and carry project materials from the nearest road or carry sand from the nearest river. These contributions typically equate to 25% of the project cost.

Increasingly, more communities have been asked to contribute financially to a water project to prepare the community for the necessity of regularly contributing to a water system maintenance fund. In Bolivia, the PROSABAR foundation requires that the communities contribute 5% of the construction cost. In Guatemala, COMENSA requires that the community contribute 10% of the construction cost, which is then used to start a maintenance fund. In the WaterAid well program in Ghana, communities need to create a $100 maintenance fund in order for WaterAid to install a hand pump. (Only a small percentage of the Ghanian communities were able to create this fund and thus received only a windlass.)

Water User Fees

To pay for system operations and maintenance, the village water committee should initiate a water user fee. Ideally, this is deposited in a bank account and is used only for the water system. In Honduras, Agua para el Pueblo suggests that village water committees collect $0.70 per household per month. In Ecuador, ProPueblo suggests that village water committees collect $0.75 to $1.30 per household per month. In Nicaragua, the national water agency installs water meters on many rural water systems with household tapstands. For these Nicaraguan water systems, typical water user fees are approximately $1.30 per household per month.

There are many problems associated with collecting water user fees and starting a maintenance fund. One basic problem is that water has always been free and people are not accustomed to paying for it. Similarly, saving money for future maintenance may be a foreign concept, especially considering other more immediate financial needs. Also, local people may not trust banks or banks may be too far away. Another problem is that water committees may lack the authority to collect the water user fees and are unable to prevent people who do not pay from using public tapstands and wells. Even where water to a delinquent household can be turned off, water committees are reluctant to turn off the water of their neighbors or relatives.

For water systems with motorized pumps, collecting water user fees tends to be more successful: people can recognize the need to pay for electricity or fuel. However, the Nicaraguan organization El Porvenir sought to help a community obtain a water system that was to be supplied by a diesel-powered well pump. The community rejected this option, recognizing that they could not afford to pay a water user fee of $1.00 per month per household to cover the cost of diesel.

Water Vendors

In urban or peri-urban areas many people are forced to buy water from vendors. Often these are the poorest communities that are not reached by the municipal water system. In Honduras, the cost of water from vendors can be 35 times higher than the official rate (Taiko 1991). Taiko also reports that people in a rural community in Uganda spent 9% of their income on vended water.

In Ecuador, WFP has met people who pay between 150 to 350 sucres ($0.04 to $0.10) per 20 liters of water purchased from tanker trucks. This equates to a cost of $2.00 to $5.00 per cubic meter. If a household of five people limits its consumption to 50 liters per day, its monthly expenditures for water would fall between $3.00 and $7.50. Should these households purchase 45 lpcpd, the monthly household expenditure for water would be $13.50 to $33.75 per household per month—well beyond their capabilities. For these families, there are few other water supply options, as surface waters and groundwater sources disappeared during a prolonged drought.

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Village Water Treatment Technologies

Most urban water systems in developing countries have treated water supplies. In these cities the prevalence of waterborne diseases can be attributed to contamination being introduced into the water distribution system, the failure of the water system to serve the entire urban population, and the absence of adequate sanitation. In rural villages there is little treatment of drinking water and there may be a lack of awareness that many diseases are caused by drinking contaminated water.

As an introduction to the topic of village water treatment, this section begins by providing information on international drinking water standards and a discussion of the relative purity of various water sources. This section also examines the reasons for the lack of water treatment in rural villages. Subsequently, water treatment technologies used in villages are described. This section also includes an overview of conventional treatment technologies used for surface water treatment and desalination processes.

Water Quality Standards

Water quality standards, goals, and guidelines have been established by individual governments and WHO (AWWA 1990). In recent years, an increasing number of water standards have been developed for new water contaminants. WHO has guidelines for five categories of contaminants in drinking water: (1) microbiological and biological water quality; (2) inorganic constituents of health significance; (3) organic constituents of health significance; (4) aesthetic quality; and (5) radioactive quality. A complete listing of the contaminants and guideline values is provided in Appendix D.

Microbiological and Biological Water Quality

Because of the high incidence of diarrheal diseases caused by drinking water that contains pathogenic organisms, this is the category of primary importance to village water systems. The coliform group of bacterial organisms is used as an indicator of fecal contamination in the water. Fecal coliform bacteria are primarily nonpathogenic and reproduce in the intestines of warm-blooded animals. Nonfecal coliforms are found in soils. In a disinfected water supply no coliforms should be present. WHO guidelines for unpiped water supplies permit coliform of nonfecal origin but do not permit fecal coliform.

Inorganic Constituents of Health Significance

This category of WHO guidelines includes constituents such as arsenic, cadmium, nitrate, lead, and sodium. Most can occur naturally in groundwater or surface waters, but may result from industrial activity and agricultural practices. For example, nitrate concentrations in groundwater are usually the result of nitrogen fertilizers. A dilemma in eastern India is the high, naturally occurring concentration of arsenic in village wells.

Organic Constituents of Health Significance

This category of WHO guidelines consists of 22 organic compounds such as benzene, phenols, and DDT. The EPA's list of regulated organic contaminants is far more extensive than WHO's list. The origins of these compounds are industrial activity and agricultural practices. Water treatment for organic compounds tends to be complicated, and efforts should be made to protect water sources from organic contamination.

Aesthetic Guidelines

Certain constituents of water do not have known health effects, but can affect the taste, odor, usability, or treatability of drinking water. This group includes total dissolved solids (salts) that affect taste, iron that can stain bathroom fixtures and laundry, hardness (calcium and magnesium) that can scale water heaters, and turbidity that can affect the efficiency of water disinfection processes.

Radioactivity Guidelines

Radioactivity in water is primarily caused by natural sources and is usually limited to groundwater sources. Except for radon, treatment processes for radioactivity tend to be too expensive for developing country villages.

Status of Water Treatment in Rural Developing Country Villages

Most water systems in developing country villages do not employ water treatment to meet the water standards presented in the previous paragraphs. The following paragraphs explore the factors that contribute to this rarity of water treatment in developing country villages.

Treatment Not Needed

Springs and groundwater are the most desirable water sources for village water systems, because they are typically free of microbiological contamination. When the use of a surface water source is mandated, efforts are made to pipe water from upstream of any potential human sources of contamination. When required and possible, the usual treatment for either type of water source is disinfection with chlorine.

Importance of Water Quantity over Water Quality

Some public health professionals assert that increased water availability and consumption should be emphasized instead of water quality, because many diseases that affect people in developing countries are called water-washed infections that result from a lack of water for personal hygiene. Table 3 classifies diseases as either waterborne or water-washed infections. The prevention of water-washed infections depends on the availability, access, and quantity of the domestic water supply rather than on water quality. Therefore, drinking water development should include hygiene education that promotes the increased use of water (Cairncross 1988).

Problems with Treatment System Sustainability

The life span of a water treatment depends on the motivation of the local people to maintain the water system, the technical and managerial capacity within the community, the support and training provided to the village, and the availability and cost of replacement parts and chemicals (i.e. chlorine). Unfortunately, few villages and implementing agencies fulfill all the requirements needed for a sustainable water treatment system.

On the village level, people may not recognize that diseases come from drinking contaminated water and may not be motivated to treat for "invisible" contaminants. Similar to village water supply systems, the sustainability of village water treatment systems will be strengthened through a hygiene education project component and long-term support to the community by development agencies.

In addition, water treatment may be prohibitively expensive. As discussed in Village Water Supply Technologies, communities usually struggle to collect water user fees for operations and maintenance.

Water Quality and Treatment as Functions of Water Source

Groundwater

As mentioned previously, groundwater, including water from springs, is typically free of pathogens, as pathogenic organisms have a short life span in an aquifer. An exception is that pathogens are more mobile in groundwater that flows through fractured rock. Many groundwater systems should be disinfected to safeguard against pathogens that could enter the water supply during distribution and storage.

When contaminants such as industrial pollutants, radioactivity, or arsenic are present in significant concentrations in groundwater, sophisticated treatment systems are required. For such contaminants, the implementation of sustainable treatment systems in developing country villages could present a major challenge, especially if there is a need to treat a large number of village wells.

Surface Water

U.S. government regulations require the filtration of all surface water sources to guard against pathogens that resist disinfection. Through water filtration and disinfection processes, pathogens and other particulates are removed from the water. This should result in a bacteriologically safe drinking water. Ideally, villages that use surface water sources should also employ filtration and disinfection processes unless the water source can be protected from contamination. The subsection entitled, Filtration Processes Used in Developing Country Villages, overviews several filtration technologies, including slow sand filtration (SSF), that have been successfully used in such villages.

Figure 4 provides guidelines for selecting the treatment process for surface water sources depending on the source water turbidity and the *Escherichia coli* bacteria concentration. Turbidity, in nephelometric turbidity units (ntu), is measured by how well light passes through the water (water clarity). *E. coli* bacteria is a type of fecal coliform used as an indicator of fecal contamination from warm-blooded animals.

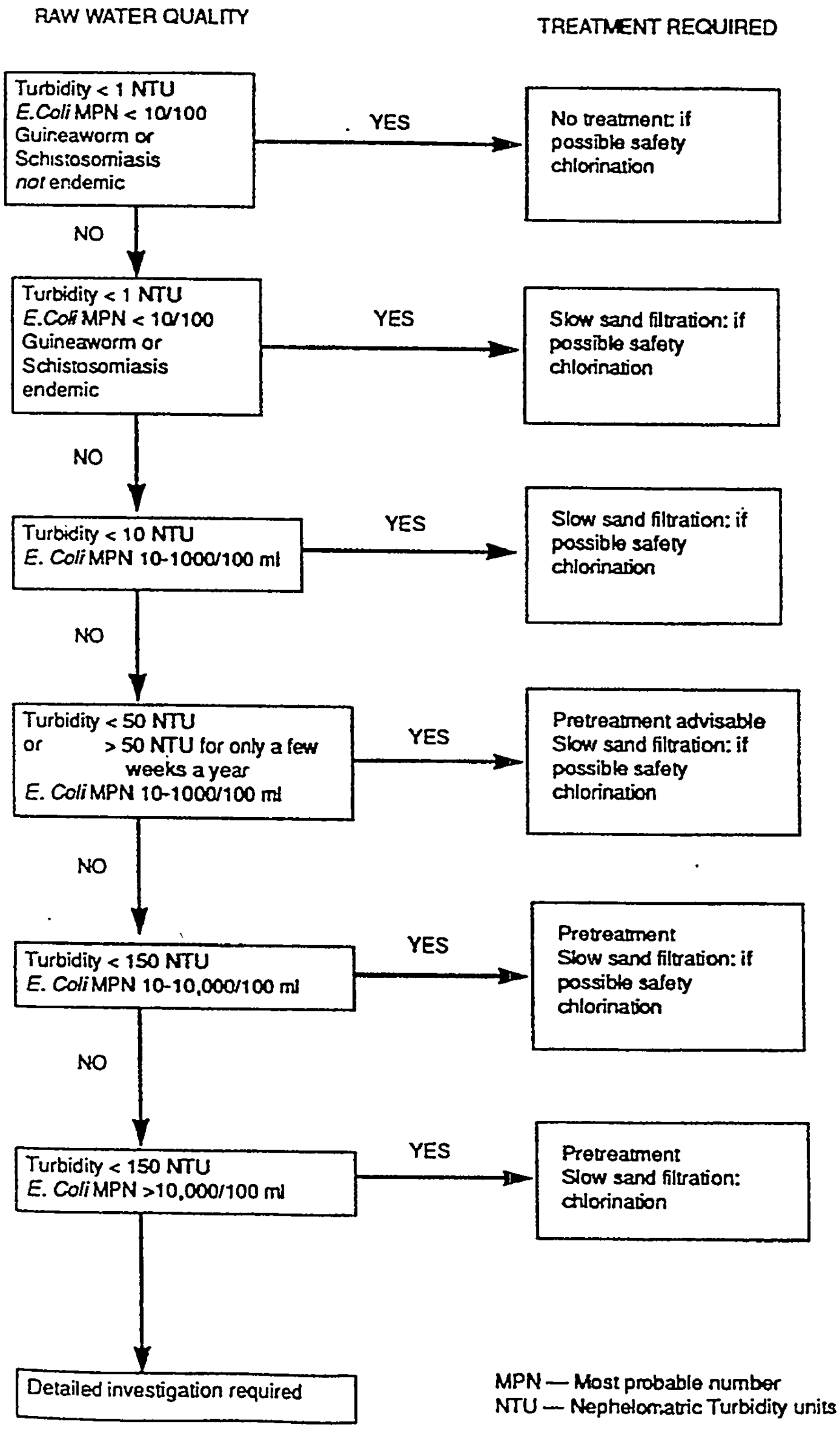
Disinfection Processes Used in Developing Country Villages

Because of safety concerns, gas chlorination systems used in the United States are only rarely acceptable in developing country villages. In villages, water can be disinfected using a chlorine (hypochlorite) solution that is made from high test hypochlorite (HTH) powder or liquid bleach. Chlorine can also be generated on-site by using electrolysis to create chlorine from a brine solution (Schultz 1984). Chlorine is preferable to other disinfectants because of its availability, cost, and ability to leave a residual in the drinking water. A chlorine residual will kill pathogens introduced into the water during storage and use.

The required time for chlorine to neutralize pathogens is called the chlorine contact time. A chlorine contact time of 20 or 30 minutes is suggested for adequate disinfection. The chlorine demand of a particular water is the sum of the chlorine concentration that has reacted in the water and the desired residual chlorine concentration. Chlorine demand depends on the quality of the water source. Suggested chlorine residuals in drinking water range from 0.2 mg/L to 2.5 mg/L. High residual concentrations are preferable where there is a high risk of waterborne disease outbreaks.

Assuming a cost of $10 per kilogram of HTH, a chlorine dose of 1.0 mg/L, and a 45 lpcpd water consumption, the annual cost of chlorine per person is less than $0.20. The cost per cubic meter is on the order of $0.01.

Figure 4: Guidelines for Selecting a Treatment System for Surface Water
(Visscher 1990)



Household Disinfection

Household water supplies can be disinfected by distributing bottles of hypochlorite stock solution to households in the community. Members of the community then add the correct quantity of stock solution to the water being stored in their homes. Stock solutions are commonly made to have a 1% chlorine concentration.

Water System Disinfection

Water systems are usually disinfected at the reservoir tank. Hypochlorite stock solution can be added to the tank manually or though a drip chlorinator, a small box, filled with the hypochlorite solution, that continuously feeds chlorine into the tank (Figure 5).

Less common methods of chlorination include venturi orifices, tablet chlorinators, and chlorination at the well head. A venturi orifice is a constriction in a pipe that creates a pressure drop that enables a flow-proportioned chlorine dose to be introduced to the water. Tablet chlorinators release chlorine as water passes by the tablets that contain hypochlorite. Chlorine can also be added into wells either manually or with a pot chlorinator, a porous device that slowly releases chlorine into the water (Figure 6).

Even these simple systems are rarely used in villages primarily because of a lack of trained personnel to encourage their use.

Alternative Disinfectants

Boiling is a common and easy way to disinfect water but increases the use of firewood. Iodine is an alternative halogen disinfectant to chlorine but is more expensive than chlorine and reacts with food starch to create an undesirable blue color. In developed countries, ozone and ultraviolet (UV) disinfection are potential alternatives to chlorine. However, these disinfectants do not leave the residual concentration needed to kill pathogens that are introduced during water distribution, handling, and storage. Its residual capability is the main benefit of chlorination. The section on Renewable Energy Considerations discusses other alternative disinfectant methods that employ renewable energy technologies.

Filtration Processes Used in Developing Country Villages

Filtration removes suspended particulate matter including clay, silt, colloids, and microorganisms. Filtration provides treatment as the water is physically strained and bacteria on filter media break down organic matter in the water. By removing microorganisms, filtration can help disinfect the water. Although filtration processes for developing country villages are described in many books, their actual use is limited. The Water and Sanitation Consultancy Group has prepared a design of a filtration processes that will serve a village with a population of 1,000 (Azrag 1989).

Household Filtration

Filters have been constructed in 50-gallon drums. Water is added to the top of the drum and the water flows down through the sand, where it is collected by a perforated pipe at the base of the drum (Figure 7). Filters can also be constructed by placing one clay pot on top of another. The top pot is filled with sand and has a perforated bottom. Water passes through the sand in the upper pot and drips into the lower pot (Morgan 1990).

Figure 5: Drip Chlorinator (Millazo)

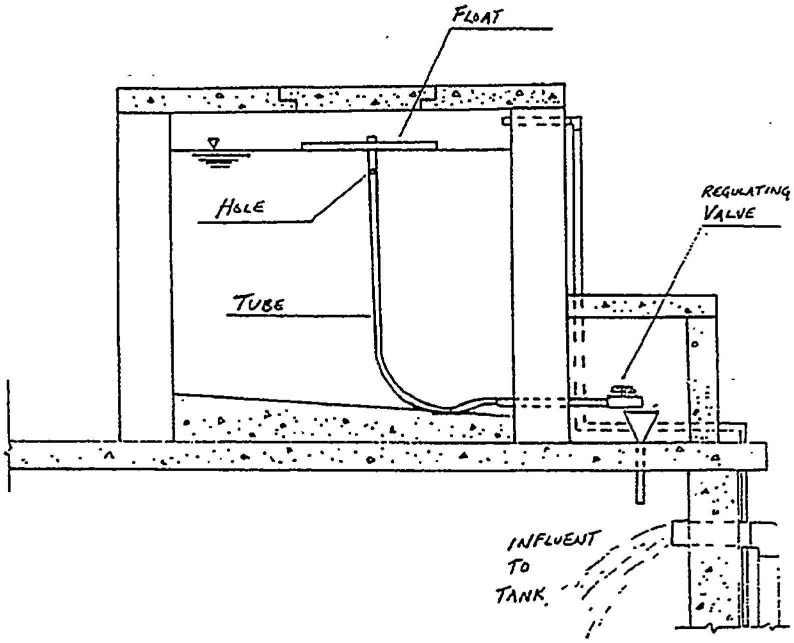


Figure 6: Pot Chlorinators for Wells or Tanks
(Pickford 1977)

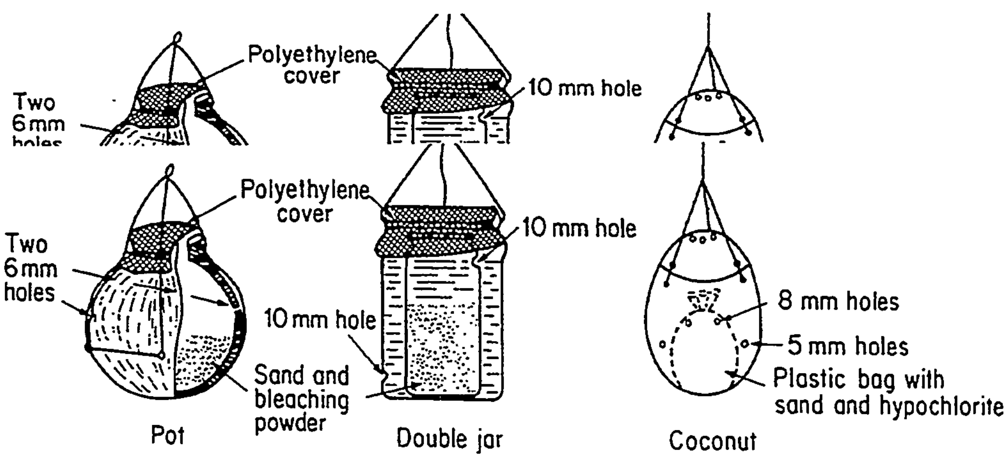
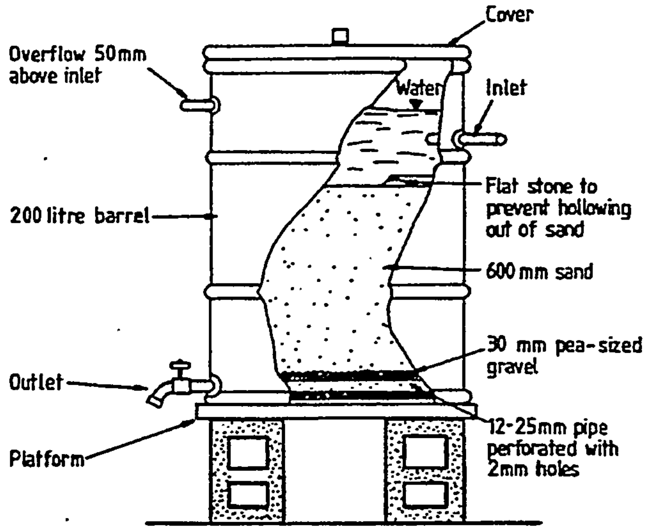


Figure 7: Household Sand Filter
(WaterAid 1993)



Infiltation Galleries

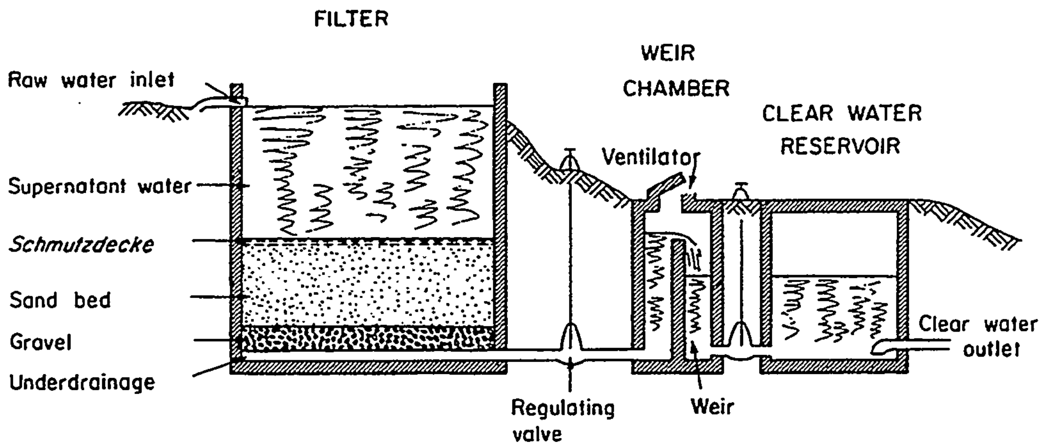
The simplest way to filter water from a stream is to build a large subsurface gallery along the bank of the stream. Water from the stream is filtered as it passes through the bank and into the infiltration gallery. This treatment method is also called bank filtration or intake filters (Wegelin 1994). Preferably, infiltration galleries would be constructed at a higher elevation than the community to allow water to flow from the gallery to the community. However, this criterion is often not achievable and infiltration galleries may need a motorized pump to pump water to the community (Pickford 1978).

Slow Sand Filters

The SSF process works well for developing country communities because it has low energy and maintenance requirements and does not require extensive operator expertise. The components of an SSF process are settling basins, roughing filters, and slow sand filter units, followed by disinfection and storage. Depending on the quality of the water source, all these components may not be needed. No electricity is required if the water source is located above the treatment facility and the community is located below it. A drawing of a slow sand filter unit is found in Figure 8. Information on slow sand filtration processes is summarized in Table 9.

Settling basins and roughing filters are often needed to treat the water before it enters the slow sand filter unit. Settling basins (sedimentation tanks) are shallow rectangular or circular tanks built to remove discrete solids by gravity. The efficiency of this process, as measured by turbidity removal, depends on the size and settling rates of the particles. The horizontal roughing filters reduce the concentration of suspended solids in the raw water before it is applied to the slow sand filters. Slow sand filters unit operate best at turbidity levels of less than 10 to 20 ntu (see Water Quality and Treatment as Functions of Water Source). Roughing filters consist of three or four chambers filed with gravel ranging in size from 25 mm to 4 mm. Water flows horizontally through the chambers, which contain successively finer gravel.

Figure 8: Slow Sand Filter
(Pickford 1978)



The slow sand filter unit consists of water being applied to the top of a 1.2-meter bed of sand, which is underlain by gravel layers that become coarser with depth. Beneath the gravel are under drains. On the surface of the bed, a thin organic layer called schmutzdecke forms. This layer removes bacteria and organic matter from the water. Slow sand filters can remove 99.9% of the pathogenic microorganisms. (In the United States, surface water treatment facilities with disinfection must remove at least 99.9% of *giardia* cysts and 99.99% of viruses.)

Maintenance of the slow sand filter unit consists of periodically raking the surface of the bed. Less frequently, the top 1 inch of sand is manually scraped from the surface of the filter. After successive scrapings to remove approximately 20 inches of sand, new sand should be added to the filter.

Conventional Surface Water Treatment

This section overviews a conventional water treatment facility; the most common process used to treat surface waters in developed countries and in urban areas of developing countries. It does not describe all possible modifications to the treatment process. A schematic of a conventional treatment process is shown in Figure 9. Representative costs are shown in Table 10.

Screens

Screens remove floating objects and suspended matter to prevent pipes from being clogged or damaged.

Pre-Sedimentation Tanks

This is an optional process used to remove sand and some silts.

Table 9: Slow Sand Filtration Unit Treatment Processes

Type of Treatment	Pretreatment Required	Target Impurity	Capital Cost per Flow Capacity ($/m^3/d)	Energy Required (watt-hr/m^3/d)	Level of Expertise to Operate *	Comment
Settling basins (WaterAid 1993)	None	Sand, some silt	$30	0.5	low	20-cm headloss
Roughing filters (Wegelin 1994)	Settling if >150 ntu	Silt, some clay	$40	0.8	low	30-cm headloss; cost assumes community participation
Slow sand filters (Logsdon 1991)	All of the above if >20 ntu	All turbidity, some micro-organisms	$50	1.7 - 3.4	medium	60–120-cm headless; cost from 15 SSS

* Labor costs associated with operation are not included. Low expertise means the process can be operated and maintained by a person with little formal education. Medium expertise means a trained operator under supervision. High expertise means a trained operator supervised by an engineer.

Coagulation

Coagulation refers to the addition of chemicals, known as coagulants, which destabilize colloidal particles that would otherwise remain in suspension. In a rapid mix tank, coagulants are added to the water and mixed for 30 to 300 seconds. Coagulants include aluminum sulfate, ferrous sulfate, lime, ferric chloride, ferric sulfate, synthetic polymers, and natural materials including plant material. Natural coagulants, such as the preparation from roots from *Maerua pseudopetalosa* (in Sudan called "kudula"), can be superior to the conventional coagulant aluminum sulfate. There are numerous other possibilities: *Moringa olefera* seeds and shells, *Acacia nilotica* (garad) shells, and *Azadirachta indica* (neem) (Azrag 1989).

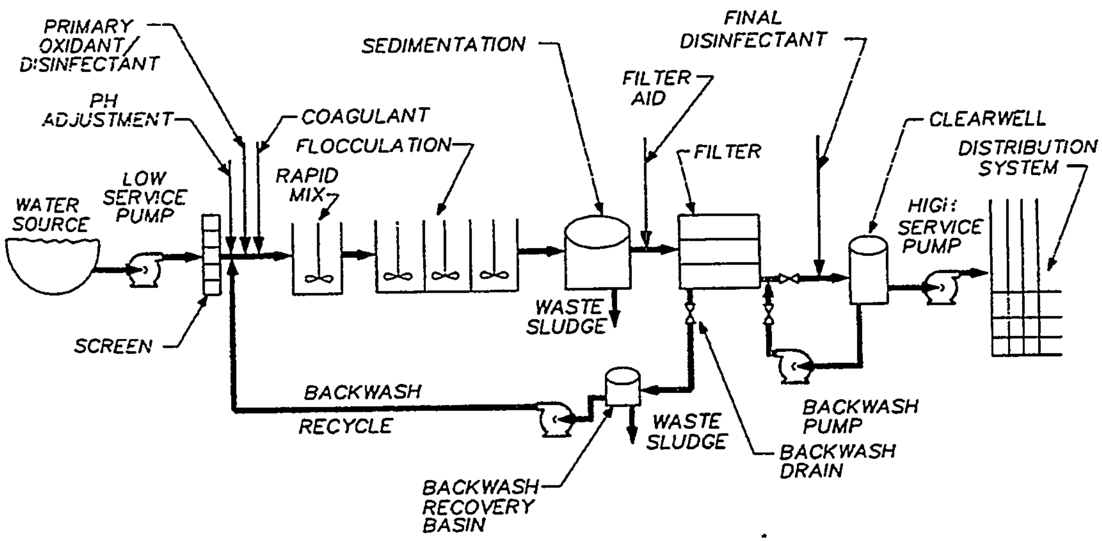
Flocculation

After coagulation occurs in the rapid mix tank, water flows to the flocculation tank. In the flocculation tank, the water is mixed slowly to promote the collision of particles. As the particles collide, they stick together and visible floc forms that can be settled or filtered in the subsequent treatment processes. Velocity gradients are often tapered in the tank to avoid shearing the large floc that forms toward the outlet end of the tank.

Sedimentation

Sedimentation tanks provide a semiquiescent environment for settling and removing grit, sand, and floc. The settled materials (sludge) can be used, or dried and landfilled, or discharged into the sewage collection system.

Figure 9: Schematic of a Conventional Treatment Facility
(AWWA 1990)



NOTE:
Chemical application points may be different than shown above. This is one potential alternative.

Filtration

Filtration is the polishing step before disinfection. Filters used in conventional treatment processes are referred to as rapid sand filters because they have higher loading rates than slow sand filters. Rapid sand filters are periodically backwashed by pumping water upward through the media.

Disinfection

The most common form of disinfection uses chlorine gas that is stored in pressurized cylinders. It is injected into water to make a high-concentration chlorine solution, which is then infused into the influent end of a chlorine contact chamber or added directly to the distribution system. The minimum chlorine contact time for adequate disinfection is 20 minutes.

Desalination Water Treatment Processes

Desalination is increasingly needed to supply water to many growing communities on islands, remote coastal areas, and arid inland areas. This option has been investigated by NREL staff member Karen Thomas. Following are excerpts from her report (Thomas, in press).

Table 10: Construction Costs for Conventional Water Treatment Facilities
(Schultz 1984)

Water Treatment Facility (Reference)	Year of Construction	Flow Capacity (m^3/day)	1997 Construction Cost*	1997 Construction Cost Per Flow Capacity ($/$m^3$/day)*
Berricil, Colombia (Arboleda)	1982	3,500	$180,000	$51
Cali, Colombia (Wagner)	1979	210,000	$5,700,000	$27
Cochabamba, Bolivia (Arboleda)	1976	12,000	$390,000	$33
La Paz, Colombia (Arboleda)	1975	12,000	$390,000	$33
Manuare, Colombia (Arboleda)	1981	2,200	$160,000	$75
Oceanside, CA (MacDonald and Streicher)	1977	220,000	$5,600,000	$26
Periera, Colombia (Arboleda)	1982	52,000	$1,300,000	$26
Parana, Brazil (Wagner)	1978	60,000	$1,500,000	$24
S30 Sao Paulo, Brazil (Azevedo Netto)	1981	2,100	$150,000	$71
Linhares, Brazil (Sperandio and Perez)	1974	2,900	$100,000	$36
Parana, Brazil (Azevedo Netto)	1975	770	$54,000	$71
Colon, Costa Rica (Institute of Water and Sewerage)	1979	450	$15,000	$33
Ramkt, India (Karkile)	1973	1,200	$24,000	$20
Chandori, India (Karkile)	1980	950	$29,000	$30

* Costs updated to present using Engineering News Record Construction Cost Indexes (ENR 1993; ENR 1997).

Figure 10 shows a general flowchart of the decision-making process for selecting a desalination technology. Solar stills work well for very small water demands (one to tens of liters per day) or in areas where no electricity or technical skills are available. More research is needed to develop rugged multiple-effect systems, which, like solar stills, would require no electricity or technical skill, but would greatly decrease the area of the distiller by reusing the heat of evaporation two to several times. Such a system could become the best desalination technology for remote villages with little available technical skill. To date, only prototype rugged multiple-effect systems have been built.

ME and multistage flash distillation (MSF) systems are the technologies of choice for areas with abundant thermal energy resources, smaller electrical energy resources, large water demands, and plentiful technical skills. In particular, ME and MSF, because of economies of scale, work best in very large-scale systems, and for use as dual-purpose plants using the waste heat of another process. The economies of scale shown in Figure 11 were calculated by least-squares regression on the range of capital costs available in the literature. Insufficient data were available for electrodialysis (ED) and mechanical vapor compression (VC) processes to estimate economies of scale.

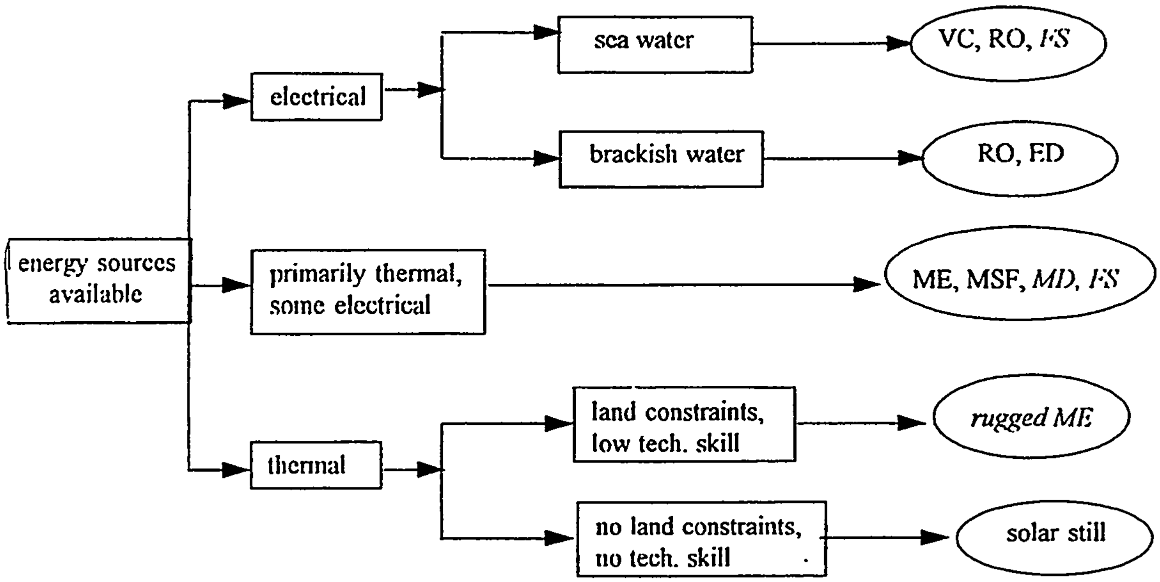
Three proven technologies require only electrical (no thermal) input: VP, reverse osmosis (RO), and electrodialysis (ED). A determination of which system works best in a given location would depend mostly on the characteristics of the feedwater available, because the cost, pretreatment, and energy requirements of membrane systems such as RO and ED depend on salinity and feedwater quality.

ED is most suited for brackish waters with low nonionic solute content; VP is energy- and cost-competitive with RO for seawater desalination. Figure 12 compares the electrical and thermal energy demands of the proven and prototype desalination methods. These systems can be made suitable for use in developing countries by incorporating rugged design features such as low recovery rates.

Table 11 summarizes desalination options. Freeze separation and membrane distillation are developing technologies that may prove competitive with the proven desalination technologies within the next decade.

Every desalination technology can tolerate intermittent operation, given proper design. In addition, all can be powered by renewable energy. Table 12 summarizes the status of renewable energy powered desalination technology. For ME and MSF, operation using solar power requires some method of thermal storage such as a hot water tank or solar pond. ED and RO demonstration plants that use PV or wind power have operated successfully using various methods to accommodate variable power, including: battery storage with an inverter to supply alternating current (AC) power to pumps; battery storage using DC pumps (no inverter required); cut-in and cut-out power levels for both PV and wind operation, with a battery to supply uninterruptible power to the control system; and, for RO, pressurized water storage from a mechanical wind pump.

Figure 10: Choosing the Appropriate Desalination Technology
(Thomas, in press)



KEY

Proven Technologies
RO reverse osmosis
ED electrodialysis
VC mechanical vapor compression
ME multiple effect distillation
MSF multistage flash distillation

Experimental Technologies
FS freeze separation
MD membrane distillation
rugged ME rugged multiple effect

Figure 11: Relative Economies of Scale of Different Desalination Technologies
(Thomas, in press)

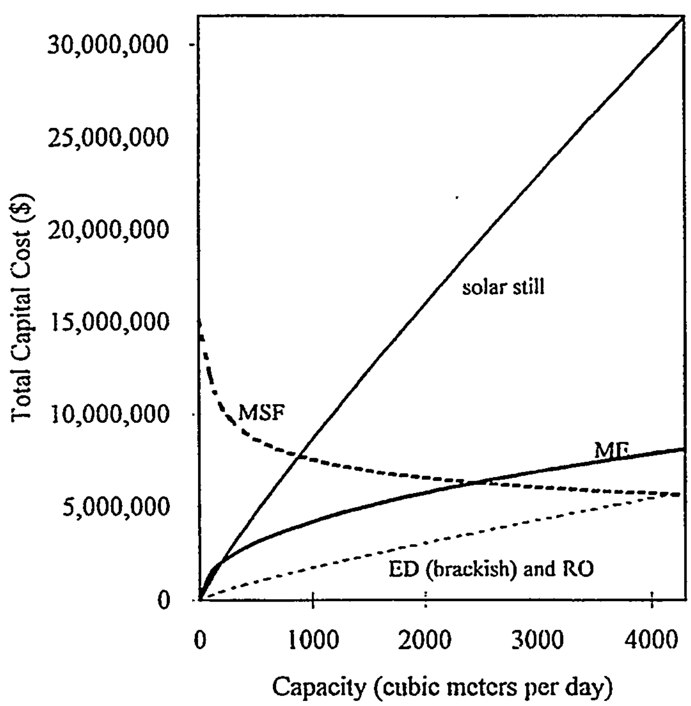


Figure 12: Electrical and Thermal Demands
(Thomas, in press)

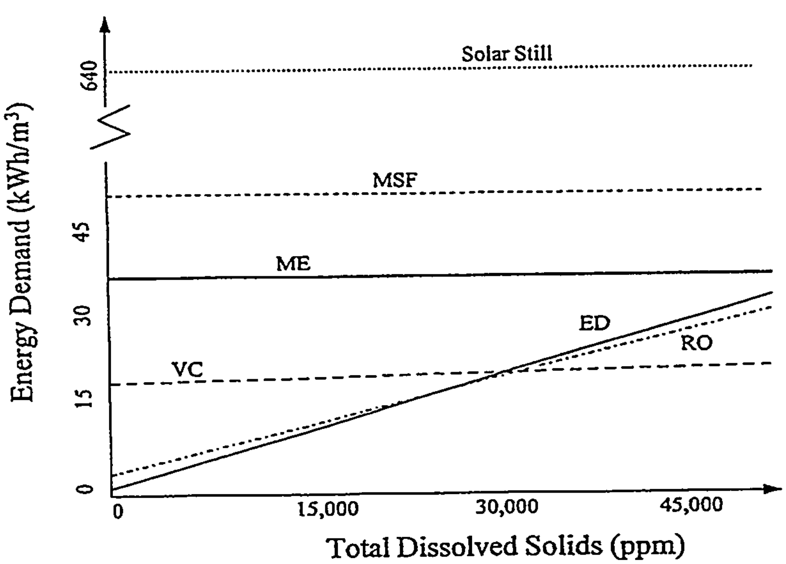


Table 11: Summary of Desalinization Options

Technology	Solar Still	Multiple Effect	Multiple Stage Flash	Vapor Compression	Reverse Osmosis	Electrodialysis	Membrane Distillation	Freeze Separation
Proven technology?	yes	yes	yes	yes	yes	yes	no	no
Energy needs	thermal	thermal and electric	thermal and electric	electric	electric	electric	thermal and electric	thermal and/or electric
Factors affecting power demand	ambient temp., wind, insulation	ambient and feedwater temp.	ambient and feedwater temp.	heat exchanger efficiency	feedwater salinity, energy recovery	feedwater salinity		ambient temp.
Energy consumption (kWh/m^3)	642	32 (thermal) 1 to 2.5 (electric)	48 to 441 (thermal) 3 (electric)	11 to 25	4 to 17	1.2 to 11	56	6 to 108
Capital cost (\$/m^3/d)	9,000 to 66,000	1,000 to 12,000	800 to 15,000	1,100 to 4,200	1,600 to 2,000	280 (brackish)	80,000	2,400
Estimated lifecycle cost (\$/m^3)	3.4 to 50	0.7 to 4	1.2 to 4.2	0.5 to 5	0.5 to 3	0.5 to 3 (brackish)		
Typical size of installation (m^3/day)	0.005 to 5	2,000 to 10,000	1,000 to 30,000	2 to 1,000	0.01 to 10,000	0.1 to 200		
Pretreatment requirements	none	Filtration, scale control, deaeration	Filtration, scale control, deaeration	Filtration, scale control	Filtration, other (depends on feedwater)	Filtration, other (depends on feedwater)	Filtration	
Maintenance requirements	Inspection and repair of leaks; dust and salt removal	Scale and corrosion control, pump maintenance	Scale and corrosion control, pump maintenance	Scale and corrosion control, pump maintenance	Replace filters, clean membranes, pump and corrosion maintenance	Replace filters, clean membranes, pump maintenance		
Operational complexity	Low	High	High	High	Depends on recovery rate and pretreatment	Depends on recovery rate and pretreatment		High (separation of ice)
Replacement requirements	None	Filter	Filter	Filter	Filter (monthly), membranes (2 to 5 years)	Filter (monthly), membranes (10 years)	Membrane lifetime unknown	none

Table 12: Development Status of Renewable Energy Powered Desalination Processes

Renewable Energy Source	Desalination Technology: Multiple Effect Distillation	Multistage Flash Distillation	Vapor Compression	Reverse Osmosis	Electro-dialysis
Solar thermal (concentrating collectors or solar ponds)	pilot plants built in Spain (1988) and Abu Dhabi, U.A.E. (1984)	pilot plants built in Kuwait (1984) and Mexico (1978)	n/a	n/a	n/a
Solar thermal (stirling engine)		pilot plant built in Texas (1987)		pilot plant built in France (1978)	
PV-battery-inverter (solar)	n/a	n/a		commercial	pilot plant built in Japan (1988)
PV, no inverter (solar)	n/a	n/a		commercial prototype developed in Australia (1996)	pilot plant built in New Mexico (1995)
Wind-battery	n/a	n/a			
Wind-diesel			pilot plant in progress in Spain	pilot plant in progress in Spain	pilot plant in progress in Spain
Wind-mechanical	n/a	n/a		pilot plant built in Australia (1990)	
Wind-electric direct drive	n/a	n/a		pilot plants built in Germany (1986 and 1979) and France (1987)	

Notes: Blank cells represent areas where demonstration plants are needed.

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Renewable Energy Considerations

Previous sections have identified issues that village water system development must address, with only a small emphasis on the energy supply issues. In this section, the emphasis is reversed to look at renewable energy aspects of these same water-related issues. Energy needs for drinking water development can be divided into two categories: energy for pumping and energy for treatment. The pumping issues are predominantly electrical or mechanical, whereas the treatment issues can be electrical, thermal, or the direct use of photons.

The report considers how each of the following renewable energy sources can be used for water supply and treatment:

- **Wind:** Generates electricity for pumping or treatment processes or mechanically pumps water
- **Photovoltaic:** Generates electricity for pumping or treatment processes
- **Solar Thermal:** Generates thermal energy for disinfection and desalination using such technologies as flat plate collectors, solar ponds, and solar concentrators
- **Biomass:** Generates thermal energy for disinfection and desalination
- **Photons:** Sunlight or artificial UV light destroys pathogens to disinfect water
- **Ocean Thermal Energy Conversion (OTEC):** Produces fresh water as process water is condensed
- **Hydropower:** Generates electricity for pumping or treatment processes or mechanically pumps water
- **Cogeneration:** Generates thermal energy for disinfection, distillation, and desalination.

These renewable energy technologies should be compared with competing energy sources in developing country villages. Principally, these are human power, animal power, small diesel- or gasoline-powered engines or an extension of an existing electrical grid. In much of the world, village-scale renewable energy technologies are able to compete against all but very short grid extensions.

A valid economic comparison of technologies is strongly dependent on the specific geographic site which is beyond the scope of this report. The primary purpose of this section is to identify special areas of opportunity at this unique intersection of a safe water supply need and a range of renewable energy technologies. This section concludes with a discussion of possible research topics.

Renewable Energy Aspects of Earlier Report Sections

Village Description

The descriptive material about villages in the section, Rural Water Supply Problems and Information on Villages, is relatively independent of technology and relates to both water and renewable energy development. This report has emphasized the similarity between water systems and renewable energy systems. In general, developing countries are installing water systems that cover an entire village rather than a collection of single-family units. NREL has similarly emphasized the need for village-scale power systems. Although there is continuing support for community water systems, in Africa there is a trend toward single-household wells to increase system sustainability and to lower costs (Morgan 1994).

Those attempting to determine whether a specific village has the requisite character for a combined water and renewable energy project, should first conduct an RRA of the village. Appendix C provides a sample set of appraisal questions.

Villages that have demonstrated the capability to operate and maintain a water system are the best candidates for renewable energy technologies. Village water supply agencies should be contacted to identify good target renewable energy markets.

Characteristics of Successful Water Projects

The section, Characteristics of Successful Water Projects, describes important characteristics of successful water projects based on the experiences of the USAID "WASH" program. These characteristics appear to be completely applicable to village renewable energy projects. For example, similar to village water projects, successful renewable energy projects depend on such program elements as the development of local institutions and the involvement of the project beneficiaries. Using indigenous NGOs to help implement water-related renewable energy programs is uncommon is especially recommended.

Water Supply Technologies

This section describes four common types of village water systems. One requires an energy source for pumping water. Renewable energy pumping technology using wind or solar power is well understood by NREL and is therefore not elaborated on in this report. However, planners of water projects are not similarly aware of the present-day capabilities and costs of renewable energy systems, and education programs in the local language should be encouraged.

Water Treatment Technologies

This section describes several water quality issues that must be considered in every water project. For reasons given in Village Water Treatment Technologies, the organizations that implement village water projects do not usually include water treatment in the project design. Therefore, at present, there is little demand for any energy source for water treatment technologies. However, as increased attention is paid to water quality, renewable energy technologies can be viable alternatives to chlorine disinfection.

Because the drinking water supplies of many villages are highly saline and there are few alternative drinking water supplies, there is a growing need in many places for drinking water desalination. The subsection on Desalination Water Treatment Processes overviews desalination technologies. Almost all these technologies can use renewable energy sources.

Conventional water filtration processes may require energy for bringing water and for backwash water pumping. During a filter backwash cycle, water is forced upward through the filter bed, suspending and cleaning the filter media. Renewable energy pumping technologies can be used to slowly pump water up to a storage tank located above the treatment facility. Then during the backwash cycle, a large quantity of water can be quickly released from the storage tank.

Current Renewable Energy Technologies for Water Systems

For the benefit of prospective users, this section reviews existing water supply and treatment applications that use renewable energy sources. The following technologies are well-known to NREL, but there may be a few points of interest as they are described from a water perspective.

Wind Systems

Wind systems for mechanical water pumping or electrical energy generation are available in sizes from about 100 watts to many hundreds of kilowatts. When the wind resource is adequate, these systems are economically competitive with diesel engines. The adequacy of the wind resource is the main issue in determining a least-cost design. Unfortunately, very little attention has been given to determining the wind resource in the rural parts of most developing countries.

For periods when there is no wind, water or electricity must be stored. In addition, the cost of storage must be compared to providing a backup source of energy such as a diesel engine or possibly a solar or biomass source of energy. In general, providing a diesel backup is cheaper than providing 100% storage. For many developing country villages, the need for a diesel engine might be eliminated if water conservation measures and gathering water through traditional means can solve short-term water shortages. This option might well be preferred by village decision makers.

Photovoltaics

A PV system consists of "cells" strung together in series and parallel to generate the required voltage and current. Each cell provides approximately 0.5 volt and delivers energy at 5% to 20% efficiency. One square meter of cells produces approximately 50 to 200 watts. The efficiency is determined primarily by the solid-state material and the cell design with the higher efficiencies likely to not be cost effective (Johansson 1993).

PV systems are today more expensive than wind systems when the wind resource is adequate and the power need is large. However, knowledge of the solar resource is generally better than knowledge of the wind resource, and PV panels can be added as needed in a modular manner to optimize the design. PV systems of the size that can serve for a single rural family (one or two panels, often less than 100 watts) are apt to provide the least expensive electrical energy source, although these systems are still too expensive (at approximately $500 to $1,000) for many rural families to purchase and maintain. In a few countries, loans with low down payments are being made to increase the affordability of PV systems. Systems are also beginning to be available on a monthly lease basis.

The need to provide storage and backup energy supplies for PV systems is similar to that for wind systems. However, in most locations, the longest period without any solar input is shorter than the longest period without wind; therefore, the battery or water storage tank could be smaller in a PV system than a wind system.

Solar Thermal Systems: Flat Plate, Low Temperature

This category includes all nontracking, nonconcentrating "flat plate" solar collectors. These are typically metallic coils of tubing with a transparent front cover and well insulated on the back and sides. They can reach temperatures in excess of the boiling point, but usually operate below that point. In many developing countries they can be less expensive than in the United States because there is no danger of freezing and a thermosiphon (no pumping) approach can be used.

In the following paragraphs, three categories of treatment processes using solar thermal systems are described: distillation for desalination, distillation for high purity (using a fresh but unpure source), and disinfection through heat destruction of pathogens (i.e pasteurization).

Within the first category are various designs of solar distillation stills for desalination that have been summarized in Village Water Treatment Technologies. Simple solar stills with a wick produce 3 to 5 liters per day per square meter (Thomas, in press).

The second category is low temperature solar stills that can produce high-quality distilled water for rural health centers. Although these distillation processes may be too expensive or complex for rural villages, they may be useful to health centers where there are fewer financial restraints, more people with technical skills, and greater needs for pharmaceutical-grade water. Such a system was in commercial operation in Sudan in 1982 (Larson 1982).

The third category of solar thermal systems is the heating of water for disinfection. Jay Burch of the NREL Solar Thermal Program has prepared a proposal to carry out a solar thermal disinfection research program (Burch 1996). The key to his proposed effort is the use of a heat exchanger to greatly increase the amount of water that can be treated per unit area per unit time. The thermal energy is "recycled" allowing the treated water to exit at a low temperature by giving up its valuable thermal energy to the incoming cooler untreated water. The usual disinfection approach of a single batch being heated all day long appears to be much less cost effective and leaves unwanted heated water (Anderson and Collier 1995). Burch's development program seems highly worthy of increased NREL and international support.

Solar Thermal Systems: Solar Ponds

A solar pond heats the water in a large lined pond. Ponds can contain either saline or nonsaline water. When the water is saline, naturally stable stratification occurs with the hottest water at the lowest levels. Solar ponds are relevant to the village water system discussions of this report in that the process can be designed to generate both electricity and fresh water. Solar ponds are a favored village power research topic in Israel (Sargent 1996).

There are three ways that solar ponds could be used to treat water in rural villages. First, water in a freshwater solar pond might become sufficiently disinfected for human consumption. Second, in some climates solar pond technology could be the least-cost approach to electrical generation that then could be used to power water treatment processes. Third, solar ponds for electrical production can simultaneously produce fresh water. For electrical production, the pond's thermal energy evaporates a working fluid that is used to run a turbine/generator. In the "open cycle" means of electricity production, the working fluid used to turn a turbine is evaporated hot pond water, which provides high purity fresh water following condensation.

The optimization of solar ponds for combined electrical and water output in rural villages has apparently never been tested. Efforts of the U.S. Bureau of Reclamation in this area have generally consumed fresh water rather than generated fresh water. One exception is that at the University of Texas at El Paso (Sargent 1996).

Solar Thermal Systems: Concentrators

Concentrating solar thermal systems use reflectors, or sometimes lenses, to achieve higher temperatures. It is then necessary to continuously "track" and point the reflector at the sun. This is an essential strategy in electrical generation because of the ability to achieve higher conversion efficiency (Johanssen 1993).

Concentrating solar thermal systems have been well demonstrated for electrical generation but have not been applied in developing country villages. However, the availability of "waste" thermal energy produced by concentrating solar thermal systems can be coupled with desalination or combined thermal/electric approaches discussed later under the topic of "cogeneration."

Trough systems are concentrating, medium-temperature solar systems in which the sunlight is focused on the water with a parabolic reflector. Trough systems may be employed to heat the water to a temperature adequate for disinfection. Industrial Solar Technology of Golden, Colorado, has been developing a 30-inch width unit that might find good application in developing countries (May 1996). Troughs oriented in an east-west direction need be manually adjusted only weekly to promote optimal heating; in other orientations they can be used with devices to track the movement of the sun.

Biomass

By boiling water, the use of biomass (wood, dung, straws) is today's most widely used renewable energy technology for water disinfection. However, this is limited in many developing countries because of widespread fuel wood shortages and the relatively high cost of wood. As such, continuing this option for disinfection should not be actively encouraged.

Biomass may also be exploited through the use of biogas or anaerobic digestion; a technology that is especially widespread in China. Manure and plant material placed in an oxygen-free (anaerobic) environment can be decomposed using several common bacteria to create methane. Where this biomass approach is being used for electricity production, the waste thermal energy may be captured for disinfection.

Photon Disinfection

The photons that make up sunlight are well known to be able to kill many organisms even in the absence of a thermal rise (Bingham 1985; Blake 1994). Solar photon disinfection is an area in which NREL already has expertise. As with other solar treatment options, provisions for water storage or backup treatment technology need to accompany any installation that uses this technology.

At the simplest level, water can be disinfected in individual households by setting transparent jars of water in the sun. This method can adequately remove many pathogenic organisms as long as the sun shines for more than a few hours. With adequate foresight, disinfected water can be stored for use at night and during cloudy periods.

Water can also be disinfected with a modified fluorescent bulb—a germicidal, low pressure mercury arc lamp that supplies UV photon energy at a single highly effective wavelength (254 nm). Such systems are already commercially available and their extension to developing countries with PV or other renewable energy input is also under way (Goodwin 1996).

Ocean Thermal Energy Conversion

OTEC is similar to energy production with solar ponds. Warm surface water can be used to evaporate a working fluid, which is used to turn a turbine, with subsequent condensation of that fluid by a second much colder fluid pumped up from a lower level of the ocean. Alternatively, the working fluid can be the warm surface water. When condensed, this fresh water can be a valuable by-product of the electrical generation process.

OTEC technologies are no longer being actively studied and will affect only a relatively small number of equatorial villages. Regardless, many island communities have a strong favorable impression of the OTEC possibility, and the technology has many strong proponents in developing countries.

Hydropower and Geothermal

Hydropower is often the least-cost renewable energy approach, but its use is generally limited to mountainous terrain. Where hydropower is available, the generated electricity can be used to power water pumping and treatment systems.

Hydropower can also be used in conjunction with other forms of renewable energy. During sunny or windy days, water can be pumped uphill to a storage reservoir. Water flowing from this reservoir can then be used to generate electricity even when there is no wind.

Hydropower can also pump water directly via a hydraulic ram, a "passive" device that pumps a small percentage of the water that enters the ram uphill.

Similar to hydropower applications, geothermal systems are extremely site specific and have no known applications in water supply and treatment for small rural villages in developing countries.

Cogeneration and Mixed Systems

Cogeneration systems are designed to use the output of both electricity and thermal energy. It is virtually mandated in parts of Europe; the Sacramento Municipal Utility District has made cogeneration a top priority. With regard to water treatment, cogeneration can produce thermal energy that can be used for disinfection or desalination.

Much more common than cogeneration are mixed systems with a chosen combination of wind, PV, storage, and diesel generator backup. At a village level, the most complex part of the operation may be the diesel generator, a technology already widely in use. The NREL sponsors of this report are leaders in this mixed form of renewable energy production.

Possible Renewable Energy Research Areas

In this final section, several renewable energy research opportunities are presented.

Mechanical Wind-Powered Pumps

There is a need for research in the development of mechanical pumping technologies that can be easily maintained by villagers.

Downward Flowing Cooling Towers

Downward flowing cooling towers are reportedly able to produce fresh water from saline water while generating electricity. This does not work well for single villages, but is mentioned because of its ability to cheaply produce large quantities of fresh water.

Downward flowing cooling towers may be able to produce economical electrical energy and fresh water from saline waters. Researchers in Israel have been studying this concept for a dozen years, giving credit to Lockheed for the initial idea (WEI 1995). The basic principle is that air is cooled by evaporation, and this heavier air will fall inside the tower reaching velocities of 750 km per hour to turn large wind turbines. The proposed 350 MW, $400 million unit obtains the fresh water from condensation of the moist air on cooled surfaces. The Israeli researchers believe that a 100-meter high by 450-meter diameter tower can provide both electricity at $0.02/kWh and water at $0.40 per cubic meter. This concept is similar to solar-energy-driven updraft "wind" units that have been tested at small scale in Spain. However, besides differing in the direction of air flow, the Lockheed-Israeli scheme emphasizes freshwater from the cheap and available ocean water resource.

Solar Cookers

A combined solar cooker–disinfection or desalination unit might be applicable to rural villages in developing countries. Solar cookers might improve their efficiency with a "water bath" that will simultaneously improve heat transfer to the cook pot and disinfect sufficient water for drinking purposes.

Materials

Transparent glazings (i.e. glass) are required for several solar thermal technologies. In developing countries, virtually the only glazing option is glass because low-cost, long-lived plastic glazes and reflective surfaces are not available. Similarly, there is a need for locally available insulation. A major topic of solar thermal research in Europe is on "transparent insulation." NREL research on materials and low-cost designs using scrap and local materials could make solar thermal systems for disinfection more readily available in developing countries.

Solar Ponds and Condensation of Atmospheric Moisture

In general, solar ponds are stratified, with thermal transfer from the hot to cold zones. However, the same can be done with two ponds, with the warm pond open during the day and insulated at night while the cold pond is reversed (possibly using the same insulation) to take advantage of the very low temperature of the nighttime sky. In certain climates, the cool pond could be used to augment the natural tendency of cool surfaces to condense atmospheric moisture as dew. Condensation already is practiced in some locations to obtain fresh water. Additional research on materials and economics might be worthy of NREL support.

Tracking Systems

Solar thermal textbooks generally state that point focus systems cannot be tracked around a single axis. However, Salih Hamadto in Khartoum, Sudan has shown that this can be done if the shape of the reflector is changed a small amount every week or so (Larson 1995). This allows him to use a ground-based receiver and a simple mechanical clock drive. In Sudan, these units have been commercially sold since 1994 to replace charcoal for cooking. There seems to have been no U.S.-based research of this technology.

Stirling Engines

One of the desalination technologies mentioned is ice making (Thomas, in press). The Stirling refrigeration cycle is widely used in cryogenic applications. Until now, there has been no U.S. government support for coupling a Stirling engine and ice-making unit in one solar-driven package (no intermediate electricity).

Village Cook Stoves

A critical biomass research area for developing countries is rural stoves that burn cleanly (Baldwin 1986). In traditional cooking methods, a significant amount of energy, that might be captured for water disinfection, is lost (Larson 1996). The traditional use of biomass directly for boiling water should be discouraged because of the already excessive use of biomass and the respiratory problems associated with dirty combustion.

Photon Disinfection

The major research topic here is testing in village applications, both with natural sunlight and using UV lamps. The latter should explore using small bulbs and current PV system inverters and ballasts during daylight hours to avoid battery storage.

Photochemical Disinfection

Photocatalytic oxidation using semiconductor photocatalyses and dye sensitized processes for formation of singlet oxygen have been demonstrated to kill bacteria and viruses in water. Both have the potential to be used as solar processes for water treatment (Blake 1997).

Combined Systems

A few PV proponents advocate capturing thermal energy from PV panels. This could be an economic extension of the Jay Burch research described above.

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Conclusions and Recommendations

Rural drinking water programs have been ongoing for decades; during these years much has been learned about the implementation process that creates successful water projects. This information can be useful to NREL both in developing drinking water supply and treatment technologies and in implementing renewable energy technologies in developing country villages.

Conclusions

Sustainability Problems with Village Technology

Many village water systems are not currently working and failure rates as high as 40% are reported. Much of the blame for this poor record of water system sustainability rests with the emphasis that has been placed on construction instead of on establishing local institutions to operate and maintain the systems.

Technology Affordability

Development efforts should not create a dependency on future funding from foreign donors. The local community must be able to afford to operate and maintain the technology. In developing country villages, household incomes rarely exceed a few hundred dollars per year, which limits the ability of local people to contribute money for future operations and maintenance. Many rural water programs promote water user fees that typically range from $0.70 to $1.30 per household per month.

Sanitation and Hygiene

Village water programs should have strong sanitation (i.e. latrine construction) and hygiene education components so the health benefits of having clean drinking water supply are realized. Project sustainability is also fostered as people learn the importance of safe drinking water and sanitation.

Project Implementation Process

The social aspects of the project should be given as much attention as the technical aspects. The involvement of local people in the project planning and implementation is necessary for local people to take responsibility for the long-term success of the project.

The project village beneficiaries need to play an active role in defining their needs and in planning the project. The involvement of village women is an integral part of a water project because they are responsible for obtaining and using much of the water. The roles of the host country government include setting policy, providing training, standardizing the technology, and providing long-term technical support to villagers. Finally, the private sector's role is to manufacture and distribute the technology in such a way that communities can maintain their systems. All these statements apply equally to water projects and any renewable energy component.

Water Demand

Village water systems should be designed to provide at least 45 lpcpd. Many waterborne diseases suffered by people in developing country villages are caused by an insufficient quantity of water for adequate hygiene. By helping local people obtain water distribution points closer to their homes, a valuable increase in water consumption can result.

Water Treatment in Developing Country Villages

Most village water systems have no provisions for water treatment. Instead, most water development organizations focus on providing an adequate quantity of water from the best-quality water source. Chlorine disinfection is performed in some developing country villages. Chlorine not only disinfects the raw water source, but also destroys pathogens introduced during water handling and storage.

Opportunities for Renewable Energy Technology in Village Water Supply

Drinking water can be pumped to storage tanks economically by various types of solar- and wind-powered pumps. Water supply systems that use intermittent renewable energy technologies must address system sustainability issues and needs for water storage.

Opportunities for Renewable Energy Technologies in Village Water Treatment

Renewable energy technologies can either serve as energy sources for current treatment technologies or used to directly treat water. Renewable energy electric sources can power UV disinfection units or provide the power to pump the water needed to backwash sand filters. Viable processes by which solar energy can directly treat water in developing country villages include the use of (1) heat to destroy pathogens; (2) natural ultraviolet radiation to destroy pathogens; (3) distillation to destroy pathogens or desalinate water; and (4) photocatalytic oxidation and dye sensitized processes.

The promotion of any renewable energy technology for water treatment must consider system sustainability issues. In addition, provisions for a backup energy source or water storage need to be considered for periods when there is insufficient sunlight or wind.

Desalination is an important subset of water treatment. There are numerous available operational technical approaches, and a few are applicable to rural villages.

Recommendations

The following are suggestions that pertain to promoting renewable energy technologies for water supply and treatment in developing country villages.

Perform an evaluation of current solar and wind powered water pumping installations in developing country villages.

Because of the high failure rate of water systems in developing countries, there is a need to evaluate the success of solar- and wind-powered water pumping facilities in villages. An evaluation could determine the attributes of successful renewable energy applications. Such an evaluation could be initiated by reviewing installations described in the literature. Additional information could be collected by sending a questionnaire to NGOs and foreign universities. These groups could be asked about the local installers and the current status of any renewable energy pumping installations in the country. Based on the information obtained by this questionnaire, NREL could perform more thorough evaluations of successful and unsuccessful installations.

Collaborate on future research and project implementation with universities in developing countries.

Some universities in developing countries research water treatment and renewable energy. One such university is the Universidad Mayor de San Simon in Cochabamba, Bolivia. People at these universities are knowledgeable about the local resources and institutions and are able to work with local communities in implementing technology. The presence of universities will allow cost-effective, long-term support to communities that obtain the technology. Working with universities will also promote recognition of renewable energy technologies among scientists and engineers in the country.

Facilitate the transfer of information on renewable energy technologies for water supply and treatment.

The use of renewable energy technologies for water supply could be promoted by providing information, such as standard designs, to people who implement projects in developing countries. NREL could serve as a clearinghouse for information on renewable energy much as the University of West Virginia serves as a clearinghouse for information on small flow wastewater treatment systems under a contract from the EPA. NREL's plan to distribute such information through the Internet is an excellent start.

Obtain expertise in microbiology to quantify pathogen removal by low-temperature disinfection processes.

Passive water disinfection processes that use solar energy could find use in villages and in rural health centers. For NREL to determine the efficiency of its experimental treatment units, it needs to identify and quantify the types of microorganisms the treatment unit should remove. In addition, it should obtain information on the relationship between pathogen removal, temperature, solar flux, and time. To accomplish this task, NREL must obtain expertise in the fields of microbiology and filtration science, if not already available through the NREL Biomass and Basic Sciences groups.

Continue to investigate desalination water treatment processes.

Villagers with salty drinking water supplies will welcome any innovation that produces cost-effective desalinated water. This report recommends that NREL continue to investigate village-scale desalination processes that require a low level of technical skill and have low operations and maintenance costs.

APPENDIX A
ACCESS TO SAFE DRINKING WATER AND SANITATION BY COUNTRY
(World Bank 1994)

(percentage of population)

Country	*Access to safe drinking water*							*Access to sanitation*						
	Total			*Urban*		*Rural*		*Total*			*Urban*		*Rural*	
	1970	1980	1990	1980	1990	1980	1990	1970	1980	1990	1980	1990	1980	1990
Low-income economies														
1 Mozambique[a]	..	..	22	..	44	..	17	..	..	21	..	61	..	11
2 Ethiopia[a]	6	..	18	..	70	..	11	12	..	17	..	97	..	7
3 Tanzania[a]	13	..	52	..	75	..	46	..	..	77	..	76	..	77
4 Sierra Leone	12	14	39	50	80	2	20	..	12	39	31	55	6	31
5 Nepal	2	11	37	83	66	7	34	1	2	6	16	34	1	3
6 Uganda	22	11	33	45	60	8	30	78	13	60	40[b]	32	10	60
7 Bhutan	..	7	34	50	60	5	30	..	..	43	..	80	..	37
8 Burundi	..	23	46	90	92	20	43	..	35	19	40	64	35	16
9 Malawi[a]	..	41	51	77	66	37	49	..	83	..	100	..	81	..
10 Bangladesh	45	39	78	26	39	40	89	6	3	12	21	40	1	4
11 Chad	27	..	57	..	..	..	..	1	..	..	..	..	..	..
12 Guinea-Bissau[a]	..	10	25	18	18	8	27	..	15	21	21	30	13	18
13 Madagascar[a]	11	21	21	80	62	7	10	..	2	..	9	..	..	..
14 Lao PDR	48	21	28	21	47	12	25	..	4	11	11	30	3	8
15 Rwanda	67	55	69	48	84	55	67	..	51	23	60	88	50	17
16 Niger	20	33	53	41	98	32	45	..	7	14	36	71	3	4
17 Burkina Faso[a]	12	31	70	27	44	31	70	..	7	7	38[b]	35	5	5
18 India	17	42	73	77	86	31	69	18	7	14	27	44	1	3
19 Kenya	15	26	49	85	..	15	..	49	30	..	89	..	19	..
20 Mali	..	6	11	37	41	0	4	..	14	24	79	81	0	10
21 Nigeria	..	36	42	60	100	30[b]	22	..	..	28	..	80	..	11
22 Nicaragua	35	39	55	91	76	10	21	18	18	..	35	..	..	..
23 Togo[a]	17	38	70	70	100	31	61	..	13	22	24	42	10	16
24 Benin	29	18	55	26	73	15	43	14	16	45	48	60	4	35
25 Central African Republic	..	..	24	..	19	..	26	..	..	46	..	45	..	46
26 Pakistan	21	35	55	72	82	20	42	..	13	25	42	53	2	12
27 Ghana	35	45	..	72	63	33	..	55	26	61	47	63	17	60
28 China[a]	..	..	72	..	87	..	68	..	..	85	..	100	..	81
29 Tajikistan	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
30 Guinea	..	15	52	69	100	2	37	11	11	..	54	..	1	0
31 Mauritania	17	..	66	80	..	85	..	..	1	..	5	..	..	..
32 Sri Lanka	21	28	60	65	80	18	55	65	67	50	80	68	63	45
33 Zimbabwe	..	..	84	..	95	..	80	..	..	40	..	95	..	22
34 Honduras	34	59	64	50	85	40	48	24	31	62	40	89	26	42
35 Lesotho[a]	3	15	47	37	59	11	45	11	14	21	13	14	14	23
36 Egypt, Arab Rep.	93	84	90	88	95	64	86	..	26	50	45	80	10	26
37 Indonesia	3	23	34	35	35	19	33	13	23	45	29	79	21	30
38 Myanmar	18	21	74	38	79	15	72	36	20	22	38	50	15	13
39 Somalia[a]	15	32	36	60[b]	50	20	29	..	17	17	45[b]	41	5	5
40 Sudan[a]	19	51	34	..	90	31[b]	20[b]	..	12	12	63[b]	40	0	5
41 Yemen, Rep.	14	24	..	100	..	18	..	..	..	..	..	..	..	..
42 Zambia[a]	37	46	59	65	76	32	43	17	70	55	100[b]	77	48[b]	34
Middle-income economies														
Lower-middle-income														
43 Côte d'Ivoire	44	..	69	..	57	..	80	..	..	91	..	81	..	100
44 Bolivia	33	36	53	69	76	10	30	13	19	26	37	38	4	14
45 Azerbaijan	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
46 Philippines	36	45	81	65	93	43	72	58	72	70	81	79	67	63
47 Armenia	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
48 Senegal	..	43	44	33	65	25	26	..	3	47	5	57	2	38
49 Cameroon	32	..	44	..	42	..	45	..	..	..	..	..	..	..
50 Kyrgyz Republic	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
51 Georgia	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
52 Uzbekistan	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
53 Papua New Guinea	70	16	33	55	94	10	20	14	15	56	96	57	3	56
54 Peru	35	50	53	68	68	21	24	36	37	58	57	76	0	20

Country	*Access to safe drinking water*							*Access to sanitation*						
	Total			*Urban*		*Rural*		*Total*			*Urban*		*Rural*	
	1970	1980	1990	1980	1990	1980	1990	1970	1980	1990	1980	1990	1980	1990
55 Guatemala	38	46	62	89	92	18	43	22	30	60	45	72	20	52
56 Congo[a]	27	20	38	36	92	3[b]	2	..	6	..	17	..	0	2
57 Morocco	51	..	56	100	100	..	18	30	..	..	..	100	..	..
58 Dominican Republic	37	60	68	85	82	33	45	57	15	87	25	95	4	75
59 Ecuador	34	50	54	82	63	16	44	..	26	48	39	56	14	38
60 Jordan	77	86	99	100	100	65	97	..	70	100	94	100	34	100
61 Romania[a]	..	..	95	..	100	..	90	..	..	97	..	100	..	95
62 El Salvador	40	50	47	67	87	40	15	37	47	59	80	85	26	38
63 Turkmenistan	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
64 Moldova	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
65 Lithuania	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
66 Bulgaria[a]	..	..	99	..	100	..	96	..	..	100	..	100	..	100
67 Colombia	63	86	86	..	87	79	82	50	66	64	100	84	4	18
68 Jamaica[a]	62	51	72	..	95	..	46	94	..	..	..	14	..	..
69 Paraguay	11	21	..	39	61	10	..	..	92	47	95	31	89	60
70 Namibia	..	..	47	..	90	..	37	..	..	13	..	24	..	11
71 Kazakhstan	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
72 Tunisia[a]	49	60	70	100	100	17	31	63	55	47	100	71	..	15
73 Ukraine	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
74 Algeria	..	..	..	..	..	..	..	10	..	..	..	..	..	..
75 Thailand	17	63	77	65	..	63	85	..	45	..	64	..	41	86
76 Poland[a]	..	..	89	..	94	..	82	..	..	100	..	100	..	100
77 Latvia	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
78 Slovak Republic	..	..	..	..	..	..	..	..	..	..	..	..	..	..
79 Costa Rica[a]	74	90	92	100	100	68	84	53	87	96	93	100	82	93
80 Turkey[a]	53	76	84	95	100	62	70	..	..	92	56	95	..	90
81 Iran, Islamic Rep.	35	66	89	82	100	50	75	74	..	71	..	100	..	35
82 Panama[a]	69	81	84	100	100	65	66	73	45	85	62	100	28	68
83 Czech Republic	..	..	..	..	..	..	..	..	..	..	..	..	..	..
84 Russian Federation	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
85 Chile[a]	56	84	87	100	100	17	21	29	..	85	99	100	..	6
86 Albania	..	..	97	..	100	..	95	..	..	100	..	100	..	100
87 Mongolia	..	..	80	..	100	..	58	..	..	75	..	100	..	47
88 Syrian Arab Rep.[a]	71	74	79	98	91	54	68	..	50	63	74	72[b]	28	55
Upper-middle-income														
89 South Africa	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
90 Mauritius	61	99	95	100	100	98	92	78	94	94	100	92	90	96
91 Estonia	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
92 Brazil	55	72	87	80	95	51	61	55	21	72	32	84	..	32
93 Botswana	29	..	90	..	100	..	88	..	..	88	..	100	..	85
94 Malaysia	29	63	78	90	96	49	66	57	70	94	100	94	55	94
95 Venezuela	75	86	92	91	..	50	36	45	87	..	90	..	70	72
96 Belarus	..	..	..[c]	..	..	..	..	..	..	..	..	..	..	..
97 Hungary[a]	..	..	98	..	100	..	95	..	..	100	..	100	..	100
98 Uruguay	92	81	95	96	100	2	..	78	59	..	59	..	60	..
99 Mexico	54	73	89	64	94	43	..	23	38	..	51	85	12	..
100 Trinidad and Tobago	96	97	96	100	100	93	88	..	92	98	95	100	88	92
101 Gabon[a]	..	..	66	..	90	..	50	..	..	..	..	..	..	..
102 Argentina[a]	56	54	64	65	73	17	17	85	79	89	89	100	32	29
103 Oman[a]	..	..	46	..	87	..	42	..	..	40	..	100	..	34
104 Slovenia	..	..	..	..	..	..	..	..	..	..	..	..	..	..
105 Puerto Rico	..	..	..	..	..	..	..	..	..	..	..	..	..	..
106 Korea, Rep.	58	75	93	86	100	61	76	..	..	90	..	..	..	..
107 Greece[a]	..	..	98	..	100	..	95	..	..	98	..	100	..	95
108 Portugal[a]	..	..	92	..	97	..	90	..	..	97	..	100	..	95
109 Saudi Arabia[a]	49	90	93	92	100	87	95	29	70	81	81	100	50	30

intry	Access to safe drinking water							Access to sanitation						
	Total			Urban		Rural		Total			Urban		Rural	
	1970	*1980*	*1990*	*1980*	*1990*	*1980*	*1990*	*1970*	*1980*	*1990*	*1980*	*1990*	*1980*	*1990*
h-income economies														
) Ireland	..	96	100	..	100	..	100	..	94	100	..	100	..	100
: New Zealand	..	..	97	..	100	..	82	..	..	..	..	..	..	88
2 †Israel	..	96	100	..	100	..	97	..	..	99	..	99	..	95
3 Spain	82	90	100	..	100	..	100	..	90	100	..	100	..	100
4 †Hong Kong	..	100	100	100	100	95	96	..	94	88	100	90	..	50
5 †Singapore	..	100	100	100	100	..	..	..	80	..	80	97	..	..
5 Australia	99	..	..	..	100	..	100	..	..	..	..	100	..	100
7 United Kingdom	99	99	100	..	100	..	100	..	85	100	..	100	..	100
3 Italy	85	90	100	..	100	..	100	..	99	100	..	100	..	100
9 Netherlands	99	100	100	..	100	..	100	..	100	100	..	100	..	100
0 Canada	96	98	100	..	100	..	100	..	..	..	..	..	..	..
1 Belgium	95	98	100	..	100	..	100	..	99	100	..	100	..	100
2 Finland	53	70	96	..	99	..	90	..	72	100	..	100	..	100
3 †United Arab Emirates	..	92	100	95	100	81	100	..	80	95	93	100	22	77
4 France	92	98	100	..	100	..	100	..	85	100	..	100	..	100
5 Austria	..	80	100	..	100	..	100	..	85	100	..	100	..	100
6 Germany	..	100	100	..	100	..	100	..	..	100	..	100	..	100
7 United States	..	100	..	..	..	..	..	..	98	..	..	..	..	..
8 Norway	98	..	100	..	100	..	100	..	85	100	..	100	..	100
9 Denmark	90	100	100	..	100	..	100	..	100	100	..	100	..	100
0 Sweden	78	86	100	..	100	..	100	..	85	100	..	100	..	100
1 Japan	..	..	96	..	100	..	85	..	..	..	..	..	..	..
2 Switzerland	97	98	100	..	100	..	100	..	85	100	..	100	..	100
lected economies not included in main WDI tables														
Angola	..	26	40	85	73	10	20	..	20	22	40	25	15	20
Barbados	98	99	100	100	100	28	100	..	..	100	..	100	..	100
Cyprus	100	100	100	100	100	100	100	..	100	97	100[b]	96	100	100
Fiji	37	77	80	94	96	66	69	..	70	75	85	91	60	65
Gambia, The	12	..	77	85	100	..	48	..	..	67	..	100	..	27
Guyana	75	72	79	..	100	60	71	100	86	85	100	97	80	81
Haiti	..	19	41	48	56	8	35	..	..	25	..	44	..	17
Iceland	..	..	100	..	100	..	100	..	..	100	..	100	..	100
Iraq	51	..	77	..	93	..	41	48	..	..	..	96	..	..
Kuwait[a]	51	87	..	..	100	..	..	..	..	..	..	100	..	..
Liberia[a]	15	..	50	..	93	16	22	16	..	6	..	4	..	8
Luxembourg	..	..	100	..	100	..	100	..	..	100	..	100	..	100
Malta	..	100	100	100	100	100	100	..	97	100	100	100	84	100
Suriname[a]	..	88	68	..	82	79[b]	56	..	..	49	..	64	..	36
Swaziland[a]	..	..	31	..	100	..	7	..	..	45	..	100	..	25
Zaire	11	..	39	..	68	..	24	6	..	23	..	46	..	11

Economies classified by the United Nations or otherwise regarded by their authorities as developing.
1990 data refer to 1988; World Resources Institute 1992.
. World Resources Institute 1992.
For range estimates, see map on access to safe water in the introduction to the WDI.

APPENDIX B

THE NEW DELHI STATEMENT ON WATER SUPPLY DEVELOPMENT

A Statement

Towards a New Philosophy on Operations and Maintenance

The operations and maintenance of water supplies and sanitation in developing countries is badly neglected, so much so that many schemes have fallen into disrepair and no longer provide the services for which they were constructed. Because of this the actual coverage levels of adequate water and sanitation in developing countries is even lower than statistics would suggest. Furthermore, this low level of service has become accepted as the norm in many places. The deterioration of these valuable physical assets is a major loss to national economies which should be avoided and although most external support agencies do not fund operations and maintenance, rehabilitation projects have become an increasing part of many country support programs. Rehabilitation is the extreme form of operations and maintenance which would not have been required, or would have been postponed if regular maintenance had taken place.

This situation has come about for-a-number of reasons. Mainly, the emphasis by developing country governments and external support agencies on trying to make up the large sector deficit by providing services to those without adequate facilities, and hence the emphasis on capital construction and expansion particularly of water services. Also, because of the previous long standing tradition of some governments and external support agencies perceiving of water and sanitation as being a free social service for all, the costs of which are not borne by the user.

In order to rectify this situation and improve operations and maintenance a number of fundamental changes must take place in the agencies responsible for providing these services. First, the agencies should change their orientation and begin to perceive of their primary role as the provider of a service to people and not the constructor of physical works. Second, the agencies themselves, which could range from a public utility to a community group, should become autonomous in efficient and transparent management and financing of the services. Third, these agencies should provide integrated water and sanitation services only in response to the effective demand of the consumer. That is, the level of services for which the consumer is willing to pay for in order to ensure good public health and environmental standards for the community.

In order to ensure the long term sustainability of water and sanitation services an awareness should be created which recognizes that maintenance is an essential component of successful development and resource utilization. Furthermore, the above principles should be embodied in the projects, policies and practices of the agencies responsible for providing water and sanitation, and the external support agencies who assist them.

This statement reflects the findings and deliberation of an operations and and maintenance working group meeting held in Geneva during June 1990.

"SOME FOR ALL RATHER THAN MORE FOR SOME"

The New Delhi Statement

Safe water supplies and environmental sanitation are vital for protecting the environment, improving health, and alleviating poverty. Disease, drudgery and millions of deaths every year are directly attributable to lack of these essential services. The poor, especially women and children, are the main victims.

Concerted efforts during the 1980s brought water and sanitation services to hundreds of millions of the world's poorest people. But even this unprecedented progress was not enough. One in three people in the developing world still lack these two most basic requirements for health and dignity.

Every developing country learned its own lessons during the International Drinking Water Supply and Sanitation Decade (1981-1990). The global community must now more effectively combine these experiences with a renewed commitment to sustainable water and sanitation systems for all. Access to water and sanitation is not simply a technical issue; it is a crucial component of social and economic development. Sustainable and socially acceptable services can be extended by using appropriate technologies, adopting community management and enhancing human resources.

Political commitment is essential and must be accompanied by intensive efforts to raise awareness through communication and mobilization of all sections of society.

Challenge

Entering the 1990s, governments face formidable challenges. Population growth continues apace. Infrastructure in many cities is stretched to breaking point. Uncontrolled pollution is putting greater stress on the living environment. Depletion and degradation of water resources are causing the costs of new water supplies to escalate. Without fundamentally new approaches, the broadscale deprivation will turn into an unmanageable crisis.

Creating the right conditions for accelerated progress will often involve profound institutional, economic and social changes, as well as reallocation of resources and responsibilities at all levels.

To achieve full coverage by the year 2000 using conventional technologies and approaches would require five times the current level of investment. However, there is a realistic two-pronged alternative:

(1) Substantial reduction in costs of services, through increased efficiency and use of low-cost appropriate technologies.

(2) Mobilization of additional funds from existing and new sources, including governments, donors and consumers.

If costs were halved and financial resources at least doubled, universal coverage could be within range by the end of the century.

Guiding Principles

For countries taking up this challenge -- "Some for all, rather than more for some", the New Delhi Global Consultation recommends four Guiding Principles:

1. Protection of the environment and safeguarding of health through the integrated management of water resources and liquid and solid wastes.

2. Institutional reforms promoting an integrated approach and including changes in procedures, attitudes and behaviour, and the full participation of women at all levels in sector institutions.

3. Community management of services, backed by measures to strengthen local institutions in implementing and sustaining water and sanitation programmes.

4. Sound financial practices, achieved through better management of existing assets, and widespread use of appropriate technologies.

Principle No. 1: The Environment and Health

Safe water and proper means of waste disposal are essential for environmental sustainability and better human health, and must be at the center of integrated water resources management.

Rapid population growth and accelerating urbanization, threaten health and the environment, presenting governments with daunting challenges in the 1990s. The poor, especially women and children, will continue to be the hardest hit.

Every day, water related diseases cause the deaths of thousands of children, and untold suffering and loss of working time for millions. Safe water combined with improved hygiene and better nutrition can reduce, and sometimes even eliminate these diseases.

The dramatic reduction of dracunculiasis (Guinea worm disease) has resulted from the provision of improved water supplies and hygiene education in endemic areas. The target of total eradication by 1995 should be fully supported. Affected countries should accord it high priority in investment programmes.

Toxic and industrial wastes pose increasing dangers to the environment in developing countries. They represent a significant threat to human health through direct contact and the pollution of water and soil. Governments and responsible agencies must take steps to control these health hazards.

Improvements to the household environment can be best achieved through the community's involvement as an equal partner with government and sector agencies. This means building on indigenous knowledge, so that policies and programmes are credible and relevant to the beneficiaries. Emphasis must be placed on education, social mobilization and community participation.

Proper drainage and disposal of solid wastes have a major impact on the neighbourhood environment. New solutions are needed which are environmentally appropriate and affordable to the communities they serve and which also conserve water resources and minimize pollution.

Integrated water resources management is necessary to combat increasing water scarcity and pollution. This includes water conservation and reuse, water harvesting, and waste management. An appropriate mix of legislation, pricing policies and enforcement measures are essential to optimise water conservation and protection.

<u>Principle No.2: People and Institutions</u>

Strong institutions are essential for sustainable development.

They require sound management, motivated people and an enabling environment of appropriate policies, legislation and incentives. Institutional development takes time. The short term achievement of production targets should not take precedence over the need for capacity building. The overall objective is achieving sustainable facilities which are used effectively by the beneficiaries.

A changing role of government is envisaged, from that of provider to that of promoter and facilitator. This will enable local public, private and community institutions to deliver better services. Decentralization demands a strong policy and support role from central governments, while local private enterprise can assist in improving the efficiency and expansion of service delivery.

The special role in development of non-governmental organizations (NGOs) and of volunteers must be acknowledged and strengthened. NGOs are flexible, credible, ready and able to experiment with innovative approaches. Governments should support the NGOs in replicating these approaches, and include NGOs, wherever appropriate, as partners in projects.

Human resources development (HRD) at all levels, from community members to politicians, is essential to institutional development. Training of professionals, managers, technicians and extension workers builds competence and confidence. Information, education and communication strategies must be integrated within HRD policies. Women must be trained and guaranteed equal employment opportunities at all levels of staff and management. National professional associations can play an important role in better HRD.

Education is a key part of the new approach. Schools offer a vast, most receptive audience for hygiene education. Polytechnics and universities already include water and sanitation related subjects in their curricula, but must be encouraged to respond to this sector's needs for multidisciplinary skills. Sanitary and environmental engineering curricula should incorporate substantial elements of community development, communications, appropriate technology, and project management.

Principle No. 3: Community Management

Community management goes beyond simple participation. It aims to empower and equip communities to own and control their own systems.

Community management is a key to sustaining services for the rural poor and is a viable option for poor urban settlements. Governments should support community management, through legislation and extension, and give it priority in national sector strategies for the 1990s.

Communities should have prominent roles in planning, resource mobilization, and all subsequent aspects of development. Within these strategies, gender issues will be all important. Women should be encouraged to play influential roles in both water management and hygiene education. Capacity building is necessary to make community management effective and enable women to play leading roles.

Linkages must be established to ensure that national plans and programmes are responsive to community needs and desires. Methods for evaluating community management have been developed for rural areas. They should now be adopted at the national level and implemented through participatory monitoring and evaluation techniques.

Principle No. 4: Finance and Technology

Given the number of people unserved and the growing demand, more effective financial strategies must be adopted in the 1990s for the long-term sustainability of the sector.

Current levels of investment in the sector are about US$ 10 billion per year.It is estimated that approximately US$ 50 billion a year would be needed to reach full coverage by the year 2000, using conventional approaches. Such a five-fold increase is not immediately feasible.

New strategies should aim towards two key objectives:

* Increased efficiency in the use of available funds

* Mobilization of additional funds from existing and new sources, including governments, donors and consumers.

Substantially increased effectiveness in the use of financial resources can yield major gains in sustained coverage. This will require changes in the way service agencies operate, to make them more cost-effective and responsive to consumer needs and demands. Involving consumers in choice of technology and service levels has proved to have a positive impact on cost recovery and sustainability.

A powerful case can be made for greater government and external support agency support. However, economic and social benefits need to be better quantified. Clear sector strategies and action plans increase the likelihood of water and sanitation programmes receiving higher priority in national planning processes. They may also make the sector more attractive for support from external support agencies (ESAs).

The high debt burden of many developing countries makes it particularly difficult for them to consider loans at market interest rates for all investments in this sector. With this in mind, lending agencies and donors are urged to look favourably on requests for grants or soft loans to support water and sanitation programmes. ESAs can also help by developing procedures or guidelines which will reduce project preparation and approval time. Support should also be given for the establishment of financial intermediaries to make credit more widely available.

Restructuring the utilization of funds for sector investments and setting of user charges are key issues in sector finance. Maximum benefits can be accrued by allocating a higher proportion of funds to affordable and appropriate projects in rural and low-income urban areas, where needs are greatest.

Rehabilitation of defective systems, reductions in wastage and unaccounted for water, recycling and reuse of wastewater, and improved operation and maintenance can often be more effective than investment in new services. Choices of technology and levels of service are major factors in determining construction, operation and maintenance costs of new projects. Due attention must be given to operation and maintenance arrangements which will ensure sustainability before investments are made.

Higher budget allocations and recovery of recurrent costs of operation and maintenance to ensure system sustainability are primary goals to be achieved. Effective cost recovery requires that sector institutions be given autonomy and authority. Further, there must be widespread promotion of the fact that safe water is not a free good. Appropriate charging mechanisms must be adopted, which reflect local socio-cultural and economic conditions. Collection should be decentralized so that revenues are available for management and operation of services.

Public sector institutions frequently default on payments for water supply and waste disposal services. For reasons of financial viability and equity, this practice is unacceptable. Increasing collection efficiency must be part of better financial management.

Research and development in developing countries has resulted in widespread application of much improved handpump and on-site sanitation technologies. The momentum established during the 1980s must be maintained and increased in the next ten years. Among the priority needs for the 1990s are improved household technologies for protecting water quality from source to mouth and low-cost wastewater disposal systems for low-income urban areas. Exchanges of information and experience among developing countries (South-South cooperation) must be further developed.

Follow-up

Implementation of the approaches outlined in this Statement will need to be part of country specific strategies.

Countries and ESAs are urged to formulate and implement action plans for water and sanitation incorporating the Guiding Principles of the New Delhi Statement. UNDP is invited to take a leading role in this process, in collaboration with other UN-system agencies.

The Water and Sanitation Collaborative Council, created immediately prior to the New Delhi Global Consultation, offers a new global forum for the exchange of information and promotion of the sector.

This New Delhi Statement will be reflected in a document to be presented to t World Summit for Children in late September 1990, along with a UNICEF-initiat statement on behalf of children, which was adopted at the Global Consultation.

The New Delhi Statement will be presented by the Government of India to the 45 session of the United Nations General Assembly in October 1990.

In addition, it is recommended that this Statement be brought to the attention of t organizers of the 1992 United Nations Conference on Environment and Development Brazil, with a request that it be tabled to emphasize the special importance of water a sanitation in environmental management.

Appendix C
Data to Be Collected during Baseline Surveys

This sample survey is based on "Achieving success in community projects," Charles Chandler, Waterlines, Vol. 5, No. 2, October 1996. The questions have been modified with some added for investigating renewable energy applications. This type of survey data is sometimes termed a "Rapid Needs Assessment" or "Rapid Rural Appraisal."

A. Community Structure

1. Village organizational structure, official and unofficial
2. Disadvantaged groups with respect to water, sanitation, and energy
3. Key leaders and influential persons within the community
4. Decision-making processes within the community, including roles of women

B. Community Economic Patterns

1. Means of subsistence and cost of casual labor
2. Preferred spending patterns and ability to pay
3. Cooperative and credit system
4. Indirect measurement of average household income (based on visual determination of housing type and sanitation practices)
5. Housing types and evident amenities including lighting means

C. Education and Communication Behavior

1. General formal and informal ways of communicating with the outside world
2. Effectiveness of various media for different tasks (entertainment, development education, traditional community events)
3. Audiovisual perceptions, literacy rates, language, and dialect

D. Water Usage, Sanitation, Management

1. Water rights and ownership and how they are obtained
2. Seasonal variations in population and water usage
3. Map of preferred water source for each household (drinking, cooking, laundry, bathing, animals, home, and garden use)
4. Time or distance traveled for water collection
5. Household water storage quantity (and source)
6. Perceptions of the community needs by the community (inclusive of disadvantaged groups, women, and children)
7. Household practices for wastewater disposal
8. Map of household defecation practices for men, women, children

E. Water and Sanitation Beliefs

1. General perceptions of community and personal illness; tolerance for disease
2. Perceived relationship between "clean" water, sanitation, and health
3. Credibility of official and indigenous medical personnel as leaders of opinions regarding health

4. Traditional beliefs concerning excreta and sanitation practices
5. Personal hygiene habits and practices

F. <u>Energy Usage</u>

1. Distance to electrical grid, and cost of extending and cost of grid's electrical energy
2. Number of operating diesels within village and within 2-hour walk, and fuel cost
3. Use of flashlights, candles, kerosene, wood, charcoal

G. <u>Water and Energy Technological Alternatives</u>

1. Data for deciding between technological alternatives (including local technical skills, capabilities and traditional alternatives)
2. Distance to nearest likely service capabilities

APPENDIX D

WORLD HEALTH ORGANIZATION WATER QUALITY GUIDELINES

TABLE 1.8 World Health Organization Guidelines for Microbiological and Biological Quality

Organism	Unit	Guideline value	Remarks
I. Microbiological Quality			
A. Piped Water Supplies			
A.1 *Treated water entering the distribution system*			
Fecal coliforms	number/100 mL	0	Turbidity <1 NTU; for disinfection with chlorine, pH preferably < 8.0; free chlorine residual
Coliform organisms	number/100 mL	0	0.2–0.5 mg/L following 30 min (minimum) contact
A.2 *Untreated water entering the distribution system*			
Fecal coliforms	number/100 mL	0	
Coliform organisms	number/100 mL	0	In 98% of samples examined throughout the year—in the case of large supplies when sufficient samples are examined
Coliform organisms	number/100 mL	3	In an occasional sample, but not in consecutive samples
A.3 *Water in the distribution system*			
Fecal coliforms	number/100 mL	0	
Coliform organisms	number/100 mL	0	In 95% of samples examined throughout the year—in the case of large supplies when sufficient samples are examined
Coliform organisms	number/100 mL	3	In an occasional sample, but not in consecutive samples
B. Unpiped Water Supplies			
Fecal coliforms	number/100 mL	0	
Coliform organisms	number/100 mL	10	Should not occur repeatedly; if occurrence is frequent and if sanitary protection cannot be improved, an alternative source must be found if possible
C. Bottled Drinking Water			
Fecal coliforms	number/100 mL	0	Source should be free from fecal contamination
Coliform organisms	number/100 mL	0	
D. Emergency Water Supplies			
Fecal coliforms	number/100 mL	0	Advise public to boil water in case of failure to meet guideline value
Coliform organisms	number/100 mL	0	
Enteroviruses	No guideline value set		
II. Biological Quality			
Protozoa (pathogenic)—no guideline value set			
Helminths (pathogenic)—no guideline value set			
Free-living organisms (algae, others)—no guideline value set			

TABLE 1.9 World Health Organization Guidelines for Inorganic Constituents of Health Significance

Constituent	Guideline value*	Remarks
Arsenic	0.05	
Asbestos	No guideline value set	
Barium	No guideline value set	
Beryllium	No guideline value set	
Cadmium	0.005	
Chromium	0.05	
Cyanide	0.1	
Fluoride	1.5	Includes both natural fluoride and deliberately added fluoride. Local or climatic conditions may necessitate adaptation.
Hardness	No health-related guideline value set	
Lead	0.05	
Mercury	0.001	
Nickel	No guideline value set	
Nitrate	10	
Nitrite	No guideline value set	
Selenium	0.01	
Silver	No guideline value set	
Sodium	No guideline value set	

*All values are in mg/L.

TABLE 1.10 World Health Organization Guidelines for Organic Constituents of Health Significance

Constituent	Guideline value*	Remarks
Aldrin and dieldrin	0.03	
Benzene	10†	
Benzo(a)pyrene	0.01†	
Carbon tetrachloride	3†	Tentative guideline value‡
Chlordane	0.3	
Chlorobenzenes	No health-related guideline value set	Odor threshold concentration between 0.1 and 3 μg/L
Chloroform	30†	Disinfection efficiency must not be compromised when controlling chloroform content
Chlorophenols	No health-related guideline value set	Odor threshold concentration 0.1 μg/L
2,4-D	100§	
DDT	1	
1,2-Dichloroethane	10†	
1,1-Dichloroethene¶	0.3†	
Heptachlor and heptachlor epoxide	0.1	
Hexachlorobenzene	0.01†	
Gamma-HCH (lindane)	3	
Methoxychlor	30	
Pentachlorophenol	10	
Tetrachloroethane¶	10†	Tentative guideline value‡
Trichloroethane¶	30†	Tentative guideline value‡
2,4,6-Trichlorophenol	10†§	Odor threshold concentration, 0.1 μg/L
Trihalomethanes	No guideline value set	

*All values are in μg/L.
†These guideline values were computed from a conservative hypothetical mathematical model which cannot be experimentally verified, and values should therefore be interpreted differently. Uncertainties involved may amount to two orders of magnitude (i.e., from 0.1 to 10 times the number).
‡When the available carcinogenicity data did not support a guideline value, but the compounds were judged to be of importance in drinking water and guidance was considered essential, a tentative guideline value was set on the basis of the available health-related data.
§May be detectable by taste and odor at lower concentrations.
¶These compounds were previously known as 1,1-dichloroethylene, tetrachloroethylene, and trichloroethylene, respectively.

TABLE 1.11 World Health Organization Guidelines for Aesthetic Quality

Constituent	Guideline value*	Remarks
Aluminum	0.2	
Chloride	250	
Chlorobenzenes and chlorophenols	No guideline value set	These compounds may affect taste and odor
Color	15 TCU†	
Copper	1.0	
Detergents	No guideline value set	There should not be any foaming, taste, or odor problem
Hardness	500 (as $CaCO_3$)	
Hydrogen sulfide	Not detectable by consumers	
Iron	0.3	
Manganese	0.1	
Oxygen, dissolved	No guideline value set	
pH	6.5–8.5	
Sodium	200	
Solids, total dissolved	1000	
Sulfate	400	
Taste and odor	Inoffensive to most consumers	
Temperature	No guideline value set	
Turbidity	5 NTU‡	Preferably <1 for disinfection efficiency
Zinc	5.0	

*Unless otherwise specified, all units are mg/L.
†TCU—true color unit.
‡NTU—nephelometric turbidity unit.

TABLE 1.12 World Health Organization Guidelines for Radioactive Constituents

Constituent	Guideline value*	Remarks
Gross alpha activity	0.1	If the levels are exceeded, more detailed radionuclide analysis may be necessary.
Gross beta activity	1	Higher levels do not necessarily imply that the water is unsuitable for human consumption.

*Units are Bq/L

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