TECHNICAL REPORT

PUMP SELECTION

A FIELD GUIDE FOR ENERGY EFFICIENT AND COST EFFECTIVE WATER PUMPING SYSTEMS FOR DEVELOPING COUNTRIES

WASH Technical Report No. 61
Revised July 1992

WATER AND SANITATION for HEALTH PROJECT

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

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Prepared for the Office of Health,
Bureau for Research and Development,
U.S. Agency for International Development
under WASH Task No. 223

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Revised
July 1992

Water and Sanitation for Health Project
Contract No. DPE-5973-Z-00-8081-00, Project No. 936-5973
is sponsored by the Office of Health, Bureau for Research and Development
U.S. Agency for International Development
Washington, DC 20523

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Abbreviations and Acronyms

AC	alternating current
ADP	animal-drawn pump
AID	U.S. Agency for International Development
ALCC	annualized life-cycle cost
ARD	Associates in Rural Development, Inc.
CIF	cost/insurance/freight (delivered price)
DC	direct current
FLFC	full-load fuel consumption
FOB	freight on board (ex-factory price)
g/kWh	grams of fuel consumed per rated kilowatt-hour
Hp	horsepower
I/V	current/voltage
J	joule
J/m^2-sec	joules per square meter per second
kW	kilowatt
kWh	kilowatt-hour
kWh/m^2day	kilowatt-hours per square meter per day (irradiation)
LPD	liters per person per day
l/sec	liters per second
mg/l	milligrams per liter
MJ	megajoules
MJ/m^2day	megajoules per square meter per day
m^3/day	cubic meters per day
m^3/h	cubic meters per hour
mph	miles per hour
MPPT	maximum power point tracker
m/sec	meters per second
MTBF	mean time between failures
MW	megawatt
NGO	nongovernmental organization
O&M	operation and maintenance
PCU	power-conditioning unit
PCV	Peace Corps volunteer
psi	pounds per square inch
PV	photovoltaic
PVO	private voluntary organization
rpm	revolutions per minute
TDS	total dissolved solids
VLOM	village-level operation and management of maintenance
W	watts
w/m^2-sec	watts per square meter per second
WASH	Water and Sanitation for Health Project
WHO	World Health Organization
W_p	peak watts

Preface

This manual was written to help engineers, economists, technical project managers, and technicians in developing countries select water pumping systems for rural and small-scale urban/peri-urban water supplies that closely match their requirements in terms of performance, cost, and long-term system support. Funding for the manual was provided by the Water and Sanitation for Health (WASH) II Project under the auspices of the U.S. Agency for International Development's (AID) Bureau for Science and Technology, Office of Health. It was prepared by the engineering staff of Associates in Rural Development, Inc. (ARD). This second (1992) edition of the manual was based on user response to the January 1989 edition, as well as courses taught by the authors to technical staff of several international NGOs and Government of Sudan water agency representatives. The manual was used as the course text.

Much of the information in this manual is based on the authors' experiences with community water systems pump testing and evaluation in a variety of developing countries, including Botswana, Indonesia, Malaysia, Sudan, Yemen, Somalia, and Djibouti. We would like to thank the many people who helped us on these projects, including host-country and expatriate engineers, economists, and technicians, as well as a number of people from private voluntary organizations (PVOs) and the Peace Corps. We would also like to thank the persons who have reviewed drafts of this report for their useful comments: Peter Bujis of CARE, Joseph Christmas of UNICEF, Mike Godfrey of CARE, Peter Lehman of Humboldt State University, Rita Kirkpatrick of ARD, ARD consultant Ron White, and Alan Wyatt of Research Triangle Institute. We would also like to thank John Ashworth (formerly with ARD) for his help in conceptualizing the early phases of this work. We appreciate the comments given to us by Peace volunteers in Benin, Morocco, Ecuador, and Kenya on revisions and corrections for this second edition. In the final stages of preparation, the first edition manual was edited by Diane Bendahmane whose careful reading and detailed comments are greatly appreciated. This second edition was produced in desktop publishing format by Andy Lowe. We would particularly like to thank Phil Roark (WASH) for his active support throughout the development of this field guide. He has not only kept the writing, shaping, and review of this guide moving forward, he has also made many useful suggestions during the development of the technical approach and presentation of the material.

This manual directly addresses four kinds of pumped water systems--diesel, wind, solar, and hand pumps. However, the methods given can be applied easily to nearly any kind of system (grid-electric, gasoline, etc.). The cost and performance data given herein represent the best available estimates as of the date of this report for the types of equipment discussed. These values can and do vary considerably, depending on the country where the equipment is used and the extent to which proper system sizing, operation, and maintenance procedures are followed.

WASH hopes this manual provides a helpful method for designing and costing pumping systems that will be useful to a wide variety of readers. Comments on the method and any additional local data on experiences with equipment, costs, performance, and availability would be welcomed by the authors.

Chapter 1: Introduction

1.1 Why This Manual?

The improvement of rural water supplies has been a major focal point of rural development efforts in developing countries. These efforts have not always met with success, in part due to inadequate operation and maintenance (O&M) and financial management, but often because of inappropriate equipment selection and use. The importance of strengthening local institutions that are capable of handling necessary equipment support functions, including system design, installation, operation, maintenance, repair, and financing, has frequently not been recognized. Even well-designed pumping systems too often fail prematurely due to a lack of planning and insufficient financing for the long-term recurrent costs of maintenance and repair.

Over the past few years, system designers have begun more systematically to consider recurrent costs (for fuel, parts, and labor) in the pump selection process, primarily in response to the rising cost and increasing scarcity and unreliability of conventional energy supplies in developing countries. Attention is also shifting to alternative energy sources for pumping, particularly in rural areas where users often do not have access to the national power grid or reliable diesel fuel supplies. In such areas, pump users have typically had only two options—diesel systems or handpumps. Increases in fuel prices over the last two decades have heightened interest in other types of low- to medium-capacity pumps, such as those powered by wind and solar energy.

This manual was written to aid a wide variety of people who are involved in making decisions about water pumping equipment and its use:

- managers of water resources development projects;
- development professionals having some familiarity with pumps;
- host-country and expatriate engineers, economists, and technicians working in both public and private sectors, including nongovernmental organizations (NGOs);
- Peace Corps (PCVs) or other volunteers with a technical background; and
- technically inclined pump users.

It is intended to enable readers to better understand and evaluate the advantages and disadvantages of different types of pumping systems and their components (e.g., pumps, engines, and controls), associated costs, and long-term O&M requirements. With this information, readers can make knowledgeable, cost-effective choices of water pumping equipment, which will result in water development projects that are more effective and that offer increased water availability and minimize costs to users. While this manual focuses on pumps for potable water supplies, it can also be used to determine pumping equipment for small to medium scale agricultural use, if irrigation water demand is known[1].

[1] See reference in Appendix A on Peter Stern, *Small Scale Irrigation*, ITDG Publications, London, 1979.

Many handbooks have been written on the subject of rural water supply, irrigation, and pump selection (see the annotated bibliography in Appendix A). Until recently, most of these focused primarily on the technical aspects of choosing a pump. Issues such as recurrent O&M costs, availability of technical skills and spare parts, system reliability, ease of installation and/or operation, and related considerations that are important to users were discussed only briefly. This manual deals not only with these issues, but also with all other major issues which are important when considering the long-term sustainability of systems.

Pump users in developing countries face a wide range of constraints in ensuring the reliability of water supplies, including:

- lack of trained, experienced mechanics and engineers to handle system design, installation, operation, maintenance, and repair;
- lack of fuel and spare parts;
- very limited selection of locally available system types and sizes to meet specific water needs;
- a sometimes wide variety of locally unsupported pumping equipment, chosen not because it meets local needs but rather because the donor prefers it;
- inadequate information on how properly to match available equipment to water pumping needs; and
- weak local, regional, and national organizations and institutions which are often unable to successfully manage and financially support water systems.

Pump selection must take all of these constraints into account. The alternative—selecting a system without being adequately informed—will undoubtedly increase water costs as well as maintenance and repair requirements. Inappropriate equipment selection can have major adverse implications for a project, including:

- inadequate or grossly over-sized system capacity;
- over- or under-used water sources;
- increased capital equipment costs;
- higher recurrent costs;
- overly frequent maintenance and repair; and
- unnecessary system downtime due to fuel shortages, inadequate renewable energy resource base, or lack of immediate access to water.

1.2 Goal and Purposes

This manual is designed to enable engineers, economists, technicians, and technical project managers who do not necessarily have extensive experience in water engineering to make appropriate choices about water pumping systems and components. It presents the decision-making process as a logical progression, first discussing what information is needed before examining pumping system alternatives, and then showing readers how to gather and analyze the needed information so it can be used in applying a set of selection criteria. To achieve this purpose, the manual attempts to:

- describe the process of properly selecting pumping equipment for small-scale water systems, based on site and resource characteristics, as well as the engineering, financial, economic, and institutional characteristics of each type of system;
- assist with the initial screening of water pumping technologies by describing what information is necessary to determine equipment needs and how to gather it;
- provide detailed guidelines for analyzing the data required for a technical comparison of diesel, solar, wind, and hand pumping systems;
- inform readers on recent and past operating experience with diesel, solar photovoltaic (PV)[2], wind, and handpump systems, including problems and new approaches to making different designs more appropriate for operating conditions in developing countries;
- give estimates of typical capital and recurrent O&M costs for the systems considered here; and
- show readers how to calculate life cycle costs of competing systems, and how to use this information to determine water tariffs (if desired).

This manual is written for a wide audience—it is not intended to be a comprehensive reference manual on the engineering and economic design and analysis of all small-scale water pumping equipment. Where appropriate, interested readers are referred to other references (see Appendix A) that contain in-depth treatments of particular topics. Here, detail has been sacrificed to provide broad coverage of all relevant areas.

1.3 Overview of the Pump Selection Process

This manual uses a method that takes into account technical, social and institutional, and cost factors in choosing the most appropriate pumping system(s) for a given level of water demand and specific set of site constraints. It focuses on the basic data needed to select any of the four system types considered here—diesel, solar, wind, and handpump systems. There are a variety of other types of pumping systems used in developing countries, including hydraulic rams, biogas-powered pumps, and animal traction pumps. These are not covered in this manual, but information on these systems is given in the bibliography (especially Fraenkel 1986). The method given here can be applied to these systems as well.

The selection process involves several stages of information gathering and analyses:

[2] There are two kinds of solar pumping systems: those which convert solar radiation into heat energy (solar thermal systems), and those which convert radiation directly into electricity (solar photovoltaics, or simply PV systems). Since solar thermal systems have not been used with success commercially, only solar PV systems are considered in this manual. The terms solar PV, solar, or PV pumps are used interchangeably.

- determining water demand at the site, based on the number, type, and consumption level of water users (e.g., human, animal, and agricultural);
- measuring and calculating the energy requirement to meet that water demand, based on the physical characteristics of the water source (head and yield, sometimes called debit) and system design;
- assessing locally available energy resources (electricity, diesel fuel, solar, and wind energy);
- reviewing what equipment is locally available or can be imported to define the range of available pumping options;
- estimating the water output of the four types of pumping systems covered in this manual—diesel, solar, wind, and hand;
- reviewing other supporting issues (e.g., social and institutional) that are important to the successful long-term operation, maintenance, and repair of pumping systems;
- determining site-specific cost factors for a financial or economic analysis that compares the life-cycle costs per unit of water delivered of competing systems; and
- based on technical and O&M considerations, determining which system best fits the community's or organization's willingness and ability to 1) pay capital and recurrent costs and 2) properly manage the system.

The pump selection process is summarized in Figure 1.

1.3.1 Determining Water and Energy Requirements

The first step in the process is to identify the physical characteristics of the site, including:

- how people are currently meeting their water needs at the site;
- the water demand profile (how much water is required, when, and how that demand changes over time);
- the head, which is basically the height you must pump the water up from its source, plus friction losses in pipes and valves;
- the water quality—is it sufficient for people to use, or will you have to develop another source?
- the available energy resources which could be used to power a pump. These could include diesel fuel (or gasoline), solar energy, wind power, or human/animal muscle power.

Then, from the examples given in Chapter 3, calculate the energy requirement for meeting the water demand. If pumps were already being used at the site and they are for some reason inadequate or broken down, talk with the pump operator (if there is one) and the people in the community and find out what went wrong. This may help prevent you from making the same mistake. To determine whether renewable energy resources are applicable at this site, you must determine from existing weather data or by installing monitoring equipment the quantity of solar radiation and wind energy available.

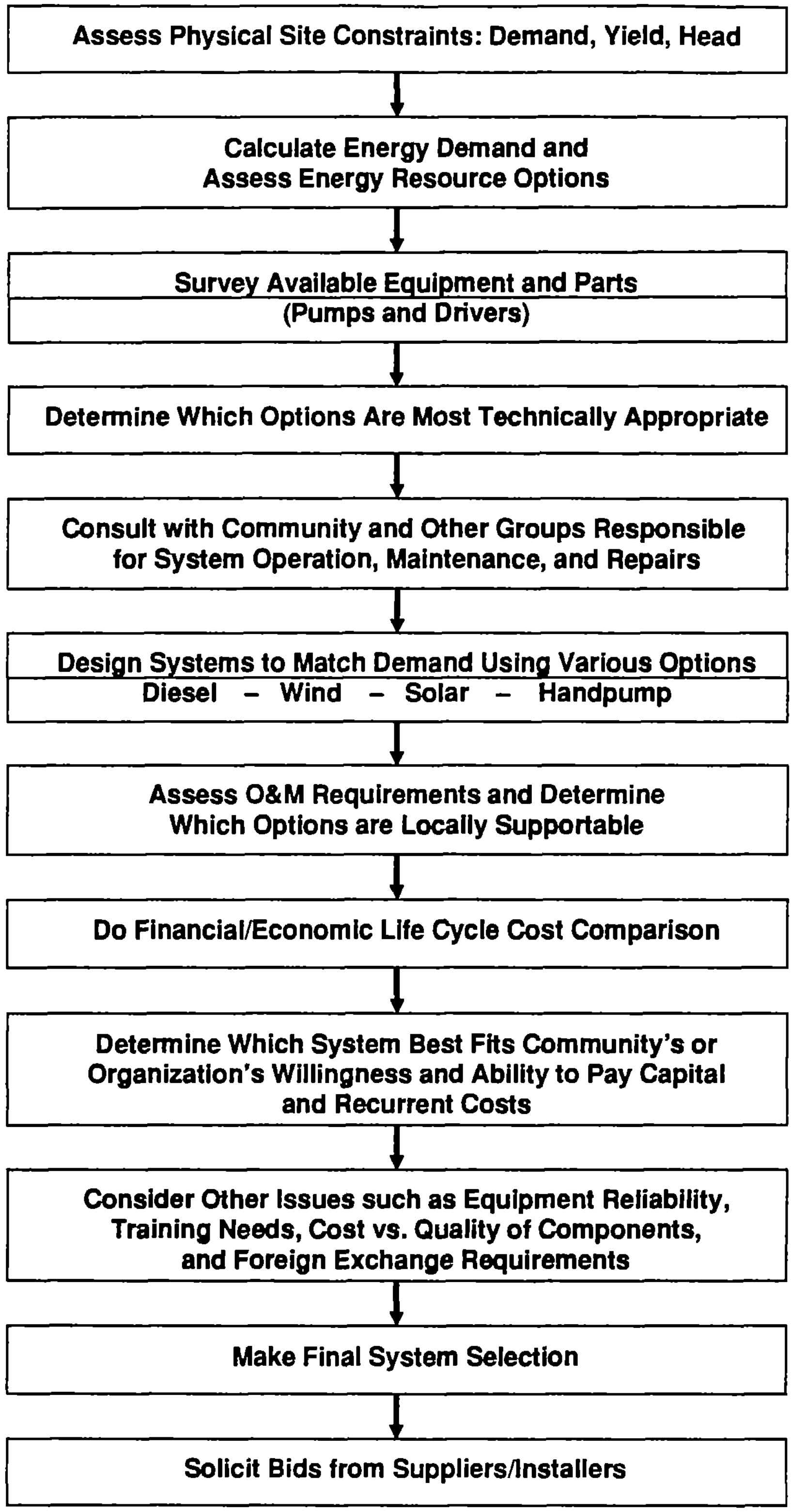


Figure 1. Pump Selection Process

1.3.2 Assessing Locally Available Equipment and Support

Check to see what kind and brands of equipment people at this or nearby sites are now using. Visit local equipment dealers to determine what types and brands of pumps, engines, and related equipment are used locally. Note power output ranges of available engines, and water output ranges and power requirements for available pumps. This information is available either from nameplates on the equipment itself, or from manufacturers' literature available from dealers. From the lists of advantages and disadvantages of different types of pumps given in Chapter 4, determine what kinds of pumps would be most appropriate for your particular situation. Note local equipment costs for a variety of different sizes of pumps, engines, and other necessary system components. Remember that a pumped water supply just may not be the best approach. In some situations, gravity systems or open wells with buckets and ropes may be the most appropriate solution. Answer the following questions:

- Do the available engine and pump power ranges fit the site energy requirement at desired flow rate and head?
- Is skilled labor available for equipment installation, operation, maintenance, and repair?
- Are local or nearby regional inventories of fuel (if required) and spare parts readily accessible at reasonable prices on a year-round basis?
- Is system design assistance available locally?
- What kind of system do the people want (communities almost always have a preference for one type of system or another)?

If pumps are already being successfully used in nearby areas, the answer to the first four questions should all be yes. If the answer to any of them is no, you should either consider other system options, or determine what needs to be done to improve the local support infrastructure, determine how much that improvement would cost, and find out who might be willing to pay for it.

For the last question, if people are forced to use a system which they never wanted, it is unlikely that the system will receive the necessary management or financial support to last very long. For a system to be sustainable over the long term, it must meet the demands of both water users and those responsible for operating and maintaining the system. All necessary support activities must be assigned to responsible groups or individuals. Where possible, identify these responsible parties as part of the equipment selection process.

1.3.3 Approximate System Design and Cost Analysis

If already available equipment appears to be a reasonable choice based on the questions in the last section, design several possible system options based on the design guidelines given in Chapters 5 through 8 for diesel, solar, wind, and hand pumps. Using the capital cost information you gathered from local equipment dealers and the recurrent cost information gathered from discussions with local water organizations, technicians, and pump operators, estimate recurrent costs. Calculate expected annual costs and the Life Cycle Cost, as discussed in Chapter 10. Then, in discussions with community representatives (preferably water committees, if they already exist) or the government agencies which will be responsible for the systems, answer the following questions:

- Can pump users or purchasing agencies raise enough money to buy the equipment outright? If not, will they have access to sufficient credit at reasonable rates to install the systems? If not, how will the system be purchased?
- Will water users (or another group or agency responsible for the system) realistically be willing and able to cover the expected recurrent costs? If so, how will the money be raised, and how will it be managed until it is used? If not, who will pay the recurrent costs?

If expected financing is not sufficient to cover expected system costs, then you must consider other options. A common example is when a community would like to be able to install a diesel pump, along with a water storage tank and distribution system. However, when realistic costs are calculated, the community may only be able practically to afford handpumps.

1.3.4 Other Considerations in System Selection

If you have determined that one or more locally available equipment options are technically suited for the application, that all necessary support activities can be provided locally, and that estimated capital and recurrent costs are within the financial and management capabilities of user or other responsible groups, there are other criteria you might want to apply to make the final choice between the remaining options, such as the following.

- **System Reliability**—There are often large differences in the quality of design and construction, materials used, and ease of installation and repair for different brands of pumping equipment. Talk to a variety of users and mechanics to find out what locally available brands are considered to be the best brands for the price.
- **Foreign Exchange Requirements**—Some systems can be purchased entirely with local currency, whereas others will require part or full payment in foreign currency. If foreign currency is difficult or very expensive to obtain in your area, you may be forced to consider only systems which can be purchased with local currency.
- **Automatic Operation**—Some kinds of systems can run essentially unattended (e.g., wind and solar systems). If labor costs are high, you should consider the tradeoff between a higher capital cost and associated savings in labor costs over the years.
- **Employment Generation**—In areas of high unemployment (especially of skilled workers), there may be good reason to consider using labor-intensive (handpumps or diesels) rather than capital-intensive (wind or solar) systems.
- **Technical or Management Training Needs**—Systems which are not widely used or are generally unfamiliar to local technicians will probably require a technical training program to enable local mechanics to properly service the new systems. Consider who will pay for this training, and how long and involved it might be.
- **Potential Environmental Impacts**—Different kinds of systems can have quite different environmental impacts (noise pollution, different effects on aquifers, greater wastewater disposal problems). Assess whether any of these might be reason for choosing one system over another.

- **Higher Quality Systems or Components**—You may want to consider using higher quality, more dependable (but probably also more costly) equipment (engines, pumps, or replacement parts) from other sources outside the immediate region. For example, replacement parts for certain diesel engines can vary in durability by a factor of five. If you can obtain higher reliability spare parts for a modest increase in cost, do so.

1.3.5 Importing Systems

If you do not feel that locally available equipment is suitable for reasons of limited selection, cost, reliability, or other reasons, consider importing systems. If you use new or locally unfamiliar systems, it will be necessary to develop an entire support infrastructure for these systems, including training people who can design, install, operate, maintain, and repair the new systems. It may also be necessary to set up new or expand existing procurement and distribution networks for equipment, parts, and fuel. Any new system would have to have advantages over existing systems which are both significant (in terms of cost and reliability) and readily apparent to users or other buyers (e.g., government agencies) to make it worthwhile to do this.

When considering new kinds or brands of equipment, again review the lists of advantages and disadvantages of different kinds of pumps and engines given in Chapter 4. Choose several different kinds which apply to your situation. Discuss with users and technicians who will provide support (e.g., system design, repairs, providing spare parts) for these systems what advantages or disadvantages are important to them. Next, look at the range of application for the systems you are considering. For example, the following table contains some useful generalizations about when and when not to use certain kinds of systems. Note that these are only very general guidelines. See Chapters 5 through 8 for details.

Table 1. System Application Guidelines

Consider Using:	For:	See:
Diesel Pumps	High head (greater than 50 meters) or medium to high volume (greater than 40 m^3/day) applications	Chapter 5
Solar Pumps	low-medium head (60 meter maximum) or low-medium volume (up to 50 m^3/day at low head) applications, and only where solar radiation levels are 5 kilowatt hours per square meter per day (kWh/m^2-day) or greater	Chapter 6
Wind Pumps	for low-medium head (60 meters maximum) or low-medium volume (5-30 m^3/day) applications, and only if average monthly windspeeds are 4 m/sec or greater	Chapter 7
Handpumps	Low volume (less than 8 m^3/day) applications at heads of no more than 50 meters	Chapter 8

After identifying several possible system options, obtain manufacturer's literature (where available) to determine the specifications of each major system component. Design several representative systems for your site using the procedures given in Chapters 5 through 8. Assess operation, maintenance, and repair needs as discussed in Chapter 9. Based on quoted costs from local or foreign dealers, do the comparative Life Cycle Cost analysis described in Chapter 10. Assess the support infrastructure as it applies to the various system options. Rank the systems according to the technical applicability, cost, probable reliability, and affordability.

Decide whether the cash flows associated with the least-cost option are acceptable. If not, go back and reconsider the other system options more carefully. If so, list the compromises you will have to make if you decide to use the least-cost system, rather than another technically acceptable, but more costly, system. For instance, less expensive equipment may have lower reliability, there may be less chance of getting repairs completed quickly, or users may be less familiar with the system. Then, decide whether any of the compromises are unacceptable to you or system users. If so, reconsider other options. If all the compromises are acceptable, go ahead and solicit bids for the system from dealers you contacted previously.

This process is intentionally somewhat repetitive, so decisions will not be made lightly or simply on the basis of first impressions or unstated assumptions. Systems that are already available locally should be favored over imported ones. Experience has shown that systems which are newly introduced without developing an appropriate support infrastructure typically fall into disrepair. This is not to say that new types of systems should be avoided. Rather, it is intended to emphasize that there are additional obstacles associated with introducing new technologies which can be insurmountable unless attention is given to developing the required support infrastructure.

1.4 Structure of This Manual

This manual is divided into 10 sections. To compare any pumping technology options, you must first determine water demand at the site. Chapter 2 shows how to calculate this. It discusses water resource characteristics that are important for system design, such as well yield (if the source is groundwater), pumping head, and water quality. After discussing demand profiles (i.e., how much water is needed and when), this chapter concludes with a subsection on important factors affecting water availability.

Chapter 3 describes how to calculate the energy requirements for meeting the demand profiles determined in Chapter 2. It discusses the general characteristics of the four types of energy considered in this manual—diesel fuel, wind and solar energy, and human power for handpumping—and recommends sources for gathering needed information on energy resources in your area.

Common types of pumping equipment and their operating characteristics are covered in Chapter 4. After water demand and head requirements are determined, the next step in the pump selection process is choosing a particular pump to match those parameters. Then, an energy source (e.g., windmill or diesel engine) is selected to provide the energy required by the pump. This chapter includes summaries of the advantages, disadvantages, and typical applications of different types of pumps and energy sources.

The next four chapters (5 through 8) focus on technical system design for the four types of energy sources considered in this manual—diesel, solar, wind, and human power. Each chapter begins with an initial description of typical equipment, followed by a discussion of system characteristics, operation, maintenance and repair requirements, and typical capital and recurrent costs. Each chapter includes a detailed example of the design of a pumping system using that technology. These examples indicate where each type of energy source can and cannot be used, based solely on technical criteria.

The final two chapters on operation, maintenance, and repair requirements and cost analysis considerations are the final stages in the screening of remaining equipment options. Up to this point, only representative costs have been given. Recurrent costs have not been analyzed, and no economic analysis has been undertaken. Chapter 10 discusses cost analysis procedures and then shows how to apply them by taking the reader through detailed examples. These examples are extensions of the technical system design cases presented in Chapters 5 through 8.

It is not necessary to read the entire manual to get help with specific decisions about pumping systems. Skip around to locate information of specific interest to you. However, all chapters should be read before equipment is selected to assure that all important selection criteria are considered.

Chapter 2: Water Demand and Resources

2.1 Demand

To select an appropriate pumping system, you must first determine the water demand at the site. The water demand (or requirement) is usually measured in cubic meters per day (m^3/day), and depends mainly on the size of human and animal populations, although it may also depend on small-scale irrigation or other uses. The amount of water used per capita depends heavily on convenience—when water is more readily available, per capita consumption will increase. Remember this when estimating future increases in demand, especially if there will be any increase in the level of service (e.g., public taps vs. in-house taps) provided.

The World Health Organization (WHO) has established the minimum water requirement for human consumption at 30 liters per person per day (LPD). In practice, while 30 LPD is often used as a design value, this is often more than the actual consumption typical of many rural areas in Africa, and much less than typically found in Latin America. Local water demand varies with location, customs and cultures, climate, distance to and capacity of the water source, water quality, and amount of effort or cost associated with meeting the demand. This section describes how to estimate current water requirements and evaluate environmental conditions that limit the quantity and quality of water which can be obtained from a given source. These data are used in the pump selection process primarily to determine pumping rate and head, and hence the system's power requirements. Information on local water demand for people, animals, and crops is often available in existing water and agricultural resources development reports for your area. You should check these reports and use that information in the demand estimation procedures given below.

2.1.1 Site-Specific Conditions

Water demand is dependent on site-specific conditions. Although general guidelines have been established by many development agencies specifying the minimum daily consumption for people, animals, and crops, actual consumption can (and does) vary considerably. This manual is intended to deal only with drinking water for people but, in fact, many village water supplies will be also used to water small livestock. Typical usage figures are given below for the most common consumers.

	People[1]	Cattle	Goats/Sheep	Poultry	Hogs	Camels
Demand in liters/day	20-40	20-40	5-15	0.2	10-15	25

1 This value assumes that people have to walk to a public tap to get their water and should be considered a minimum requirement. If house connections or in-yard taps are common, this value should be multiplied by a factor of four or more.

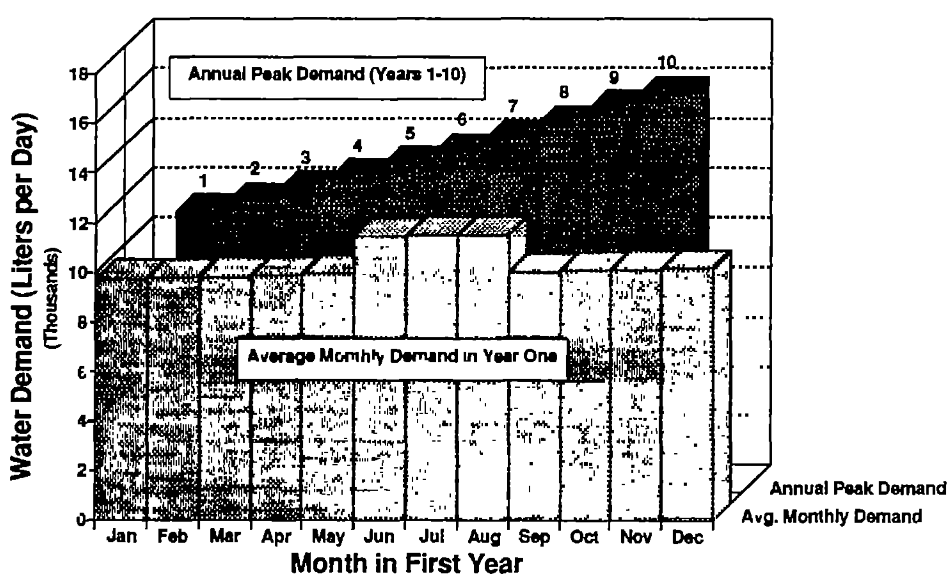
The total water demand is obtained by multiplying the number of people and animals to be served by the per capita consumption, and then adding other demands (watering gardens, selling water to nearby consumers, etc.) in the area the pump will serve (the service area). When calculating the total water demand for a service area, consider that people may keep more animals when water becomes more readily available. Also, people from surrounding villages outside the service area may want to use the new system if their own water sources fail, or if it is easier for them to get water from the new system.

2.1.2 Variations in Consumption

Water consumption can vary hourly, daily, seasonally, and annually. A demand profile refers to water consumption over time, usually a year, although the concept can be applied over the course of a day. Water demand varies depending on need as well as supply. Human beings and animals tend to drink more water in hot dry seasons. If water is available, consumption will increase at such times. (Also, if surface water is available, the demand for pumped water for animals will decrease.) Sometimes during dry seasons, local water supplies simply dry up, so consumption decreases (or completely stops) at some water points and greatly increases at those where water is still available. During dry seasons, borehole yields typically drop in regions where aquifers have low recharge rates. Nomadic people can also have significant effects on water demand, creating large "spikes" or short periods of very high demand in the profile. Water demand is not necessarily constant from year to year, due to population growth, human and animal migration, changes in size of livestock herds, droughts, and a variety of other factors. An example of two typical demand profiles is given in Figure 2. They represent the village water demand given in Example 1 on page 15. The front set of bars represents the

Figure 2.

Typical Demand Profiles
(Changes by Month and Year)



monthly average demand in Year One of the system's operation. The back set of bars represents the growth in demand over the 10 year design life of the system.

The supply profile depends on the type of pump. For example, a diesel pump normally operates at a constant rate and can deliver water at a moment's notice. The same is true of handpumps, although on a much smaller scale. Solar or wind pumps can deliver water only when the energy resource is available—when the sun is shining or wind is blowing above the windmill's start-up wind speed. This has obvious impacts on system design. For instance, suppose you want to install a solar pump, but system users want water early in the morning. To meet that portion of the daily demand profile, a storage tank is needed to reserve part of the previous day's output.

As a general rule of thumb, wind and solar pumps should be designed with three-to-four days of storage to account for the fact that they cannot deliver water on demand. While variations in demand can be managed by designing storage into a pumping system, usually this helps meet only short-term water needs (several days at most), not seasonal variations in demand. Storage tanks or basins typically hold an amount equal to a normal village's daily water demand, say 20 cubic meters. It is not usually economical to store enough water for five days given the cost of storage, particularly when using elevated storage tanks. However, people often maintain a certain level of storage in their houses, frequently around one day's supply. Determine what people's water storage habits are (or could be encouraged to be) before before sizing the storage system. If a site is so remote that it takes five or more days to fix breakdowns, the cost of additional storage must be compared to the cost of trucking in water (in the event of an emergency), higher-cost preventive maintenance to increase system reliability, backup systems, or other measures to insure water availability during system outages.

Energy resources, which are discussed in detail in Chapter 3, can also vary seasonally. For example, diesel fuel is often unavailable in remote areas during rainy seasons, when roads become impassable. Renewable energy pumping systems, such as wind and solar pumps, can deliver water only when adequate energy resources are available, not during calm or cloudy periods. Other seasonally dependent factors can affect system performance—for instance, upstream flooding could raise sediment levels in a river high enough that pumps become clogged. The possibility of annual and seasonal variations in water demand and supply should be taken into account when designing pumps. With adequate safety factors in system design, demand can usually be met most of the time. Remember that for sites where demand variability is high, no reasonably designed (or priced) system can always be expected to meet demand.

2.1.3 Growth in Demand

Estimates of system capacity require the assumption of a design period or horizon, which is typically 10 to 20 years. This can be different from the amortization period for economic comparison of different systems (see Chapter 10), as long as the potential exists for expanding the system's capacity at the end of the design period to meet future demand. All system design decisions should take into account the fact that the demand for water will probably increase over time. Demand is affected not only by population growth (people and animals), but also often by ease of access. Per capita consumption (measured in LPD) usually increases significantly only if service increases—that is, if many additional water points are installed nearer to users, particularly yard taps or in-house connections. While it is difficult to generalize without specific information on local population growth, rates of 1 to 4 percent per year are typical for rural villages in developing countries. This may sound small, but a 4 percent annual growth rate means that the demand for water will increase by over 40 percent in 10 years (not assuming any increase in per capita consumption). Increased demand due to growth in population and per capita consumption can be calculated using this formula:

$$D_F = D_P \times (1 + F_{PG})^{(N-1)} \times (1 + F_{CG})^{(N-1)} \quad \textit{Formula \#1}$$

where D_F = future demand (m^3/day)

D_P = present demand (m^3/day)

F_{PG} = population growth factor (% per year)

N = design period in years

F_{CG} = consumption growth factor (% per year)

If per capita demand remains constant, this formula simplifies to:

$$D_F = D_P (1+F_{PG})^{(N-1)}$$

The consumption growth factor (F_{CG}) would not normally be significant. It would only be used if per capita consumption increased on some regular annual basis due, for example, to steadily expanding an increased level of service throughout the community over several years.

Steadily increasing water requirements place different demands on the various types of systems. These demands are handled in different ways. For diesel or gasoline (petrol) pumps, increased demand can be met simply by increasing the flow rate (engine speed) or operating the system for more hours each day. The latter is also true for handpumps. Also, depending on the water source, additional handpumps could be installed (e.g., two handpumps could be installed on one capped hand-dug well). Solar PV and wind pumps are usually oversized relative to current demand in order to account for future increases in demand. However, this can be a costly approach, particularly for PV systems. PV pump output can be increased by adding modules to the system, up to the power limit of the motor (see Chapter 6). Once installed, wind pumps have little flexibility in meeting increased demand, so it is important to estimate growth in demand as closely as possible before sizing a wind system (see Chapter 7). Example 1 on the next page demonstrates how to estimate future demand growth.

2.2 Water Resource Characteristics

While the number of water users and their individual consumption needs are used to calculate demand, actual demand can be constrained by the available water source. The source may be surface water (e.g., rivers, lakes, and man-made or natural reservoirs) or groundwater (boreholes, dug wells, and springs). To determine what type of pump(s) can be used and the maximum demand that can be met, you must know certain specific characteristics of the water source:

- the yield of the source in cubic meters per hour or day (m^3/hour or m^3/day);
- the static water level in meters;

Example 1: Calculating Demand

A village has 300 residents, but during the summer, 50 students return home from boarding school. The animal population is 200 chickens and 75 goats. Irrigation water for gardens comes from the nearby river. Suppose the population growth rate of people and animals is 4% per year over the ten year system design period.

A) Calculate design demand, assuming no change in the level of service.

Peak demand will occur in summer, when 350 people are in the village. From the table on the first page of this chapter, per capita consumption is 30 LPD for people, 10 for goats, and 0.2 for chickens. Present demand is then:

$(350 \times 30) + (75 \times 10) + (200 \times 0.2) = 11{,}290$ liters/day

From Formula 1, future demand in ten years is:

$11{,}290 \times (1 + 0.04)^{(10-1)} =$ 16,069 liters/day (a 42% increase)

B) Recalculate design demand, assuming everything remains the same, except that yard connections are installed after five years, raising demand for people from 30 to 80 LPD.

Answer: Since the consumption rate only increases for people, it is easiest to calculate the demand for people and animals separately, then add them together. For animals, present demand is:

$(75 \times 10) + (200 \times 0.2) = 790$ liters/day

After ten years, future demand just for animals will be:

$790 \times (1 + 0.04)^{(10-1)} = 924$ liters/day

After five years, the number of people in the village will be:

$350 \times (1 + 0.04)^{(5-1)} = 409$ people

The new yard connections are then installed, so that demand increases to 80 LPD. During the last five years of the design period, demand for people therefore increases to:

$(409 \times 80) \times (1 + 0.04)^{(5-1)} =$ 38,278 liters/day

Adding the human and animal water consumption together gives a total design demand of 39,202 liters per day, *which is 3.5 times as much as the initial daily demand.* This underlines the importance of calculating the future demand when designing the system.

- the drawdown in meters (the drop in water level during pumping--see Section 2.2.2 below); and
- the quality of the water.

For pump selection, the most important characteristics are yield, static water level, and drawdown. The energy needed to pump water is directly proportional to the total pumping head (explained below) and flow rate. The pumping head depends partly on the static water level and the drawdown. The pumping rate can be so great that drawdown falls to the pump level in the well casing. As pumping rate increases, the drawdown increases, which in turn increases the energy required. Care must be taken not to over-pump the source. The maximum sustainable aquifer yield is the rate at which water can be pumped from the source without depleting it.[2] Finally, the choice of equipment may also depend on whether or not the source has significant water quality problems. For wells, if information about yield, water level, and drawdown is not available from well-completion certificates or test-pumping logs, the well must be test-pumped. Well yield can limit the short-term flow rate for pumping water (m^3/h)and, in turn, the number of hours of pumping that are required to meet demand. However, the long-term pump rate (m^3/day) should not exceed the sustainable yield of the water source. This may affect equipment selection since some types of equipment are better matched to higher (diesel) or lower (solar) pumping rates.

2.2.1 Flow Rate

Daily water demand can be met in different ways. For example, if the daily water requirement is 100 m^3/day, the entire amount can be pumped in one hour (at 100 m^3/h) or it can be pumped over the course of 10 hours (at 10 m^3/h). Pumping the water as quickly as possible saves time, but it is not always possible or advisable. Pumping at too high a rate from a source with limited yield may cause excessive drawdown. This would increase the total pumping head and would therefore require more energy; it could even cause the pump to run dry. If the water source is a year-around river, it is unlikely there would be any problem meeting small-to-moderate water requirements, except in the case of a drought. However, most wells and springs are incapable of delivering 100 m^3/h. Thus, a careful assessment of well yield and pumping rates is necessary before specifying the equipment.

For drilled and dug wells, it is important to know the maximum sustainable aquifer yield, which is the maximum rate at which water can be continually pumped on a long-term basis. This provides an upper limit for the pumping rate selected during the design process. The well's maximum sustainable yield and drawdown under these conditions are usually estimated from data obtained during the test-pumping procedure when the well is first drilled. It is difficult to determine the exact value for this yield. The actual design flowrate is usually chosen as only a fraction (50-75 percent) of the estimated well yield. This is a safety factor used to minimize the possibility of overpumping the well. Drawdown and, hence, total pumping head will be less when the pumping rate is less, and the likely drawdown for lower pumping rates often can be estimated.

Choosing a Design Flow Rate

- Determine the maximum sustainable yield in m^3/day from the water source. If this is greater than the maximum sustainable yield, you may have to develop a secondary source.
- Determine the peak daily demand for the site. If this is greater than the maximum sustainable yield, you may have to develop a secondary source.
- Depending on the type of pumpset (engine/pump) you choose, estimate how many hours you expect to operate it every day.[3]

[2] See especially *Groundwater and Wells*, Driscoll et al. 1986 for more information.

[3] For example, a diesel pump usually requires an operator who would typically work an eight-hour day. Depending on your demand, of course, you may need to operate the pump 12 or more hours a day, and get a backup operator.

- Calculate the average flow rate (in m^3/h) by dividing the daily demand by the expected operating hours of the pumpset[4].

In addition to the maximum sustainable yield for a single well, you should also consider the sustainable yield of the aquifer catchment area in which your system(s) is to be located. For example, in some developing countries (Bangladesh and Yemen are good examples), the exceedingly large number of tubewells drilled in some areas has resulted in a drastic lowering of the regional groundwater table. This happens when the total extraction of water from all of the tubewells is greater than the maximum sustainable yield of the aquifer. If historical data on groundwater replenishment rates are available, estimate what effect the pumping rate you propose (and the number of pumps you are planning to install) will have on your local aquifer.

2.2.2 Total Pumping Head

"Head" is a term used for several related quantities that together comprise the effective pressure against which a pump lifts water. Head, usually given in meters or feet of water, is a combination of the following components:

- elevation (static water level plus static discharge head plus drawdown);
- pipe friction;
- velocity; and
- pressure head.

The components of total pumping head for an unpressurized system (except velocity) are illustrated in Figure 3 and explained in greater detail below. Values for each component must be measured or calculated to determine total pumping head.

Elevation head is usually divided into three parts:

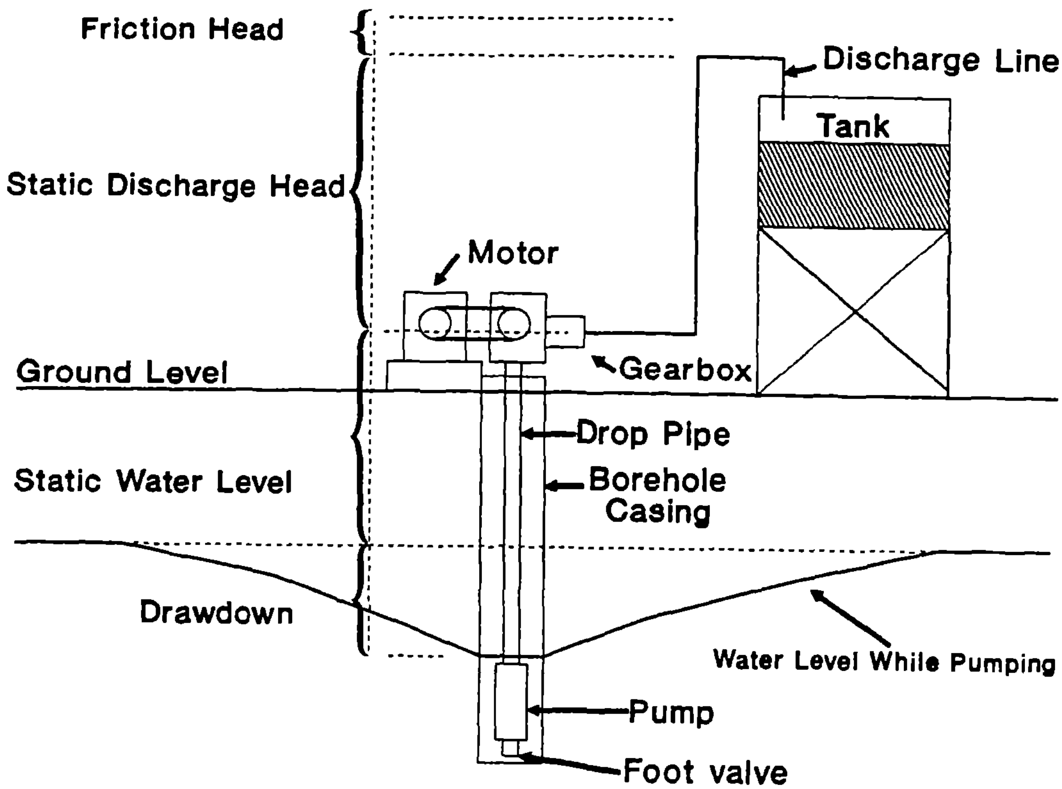
- **static water level**—the vertical distance from the water level to the surface of the ground (or the discharge point of the pump as shown in Figure 3);
- **drawdown**—the distance from the static water level to the lower dynamic water level when the pump is operating; and
- **static discharge head**—the vertical distance from the pump outlet to the highest point in the system, usually the storage tank if there is one.

Elevation

Static water level can easily be measured with battery-driven well sounders during site visits or obtained from accurate well-completion records. Static discharge head is a function of the system design (e.g., whether or not you use an elevated tank) and local topography. This component of elevation head can be measured during site visits or computed from site surveys and plans.

[4] While a diesel pump has a constant output, solar and wind pump outputs vary over the day. A solar pump typically operates over an 8-10 hour day under good sunlight conditions, so figure the average hourly flowrate (see Chapter 6). Depending on the wind conditions, a wind pump may operate anywhere from 0-24 hours a day (see Chapter 7).

Figure 3. Components of Total Pumping Head



For the size of pumps commonly used for village water supplies, the drawdown is essentially zero for most rivers and streams. With boreholes (wells), the drawdown depends on aquifer performance, well design and development, and the pumping rate. Drawdown information is available from proper test-pumping records and is often given in terms of the specific capacity (yield per unit of drawdown) of the well (measured in m^3/day/meter of drawdown, usually after 24 hours of pumping)[5]. Drawdown usually increases as the pumping rate increases, since water can usually be pumped out of the well faster than it is replaced from the surrounding aquifer in most situations.

Unfortunately, well drawdown figures often are not readily available. In such cases, test-pumping should be done on the water source before designing the system. If possible, do this during or shortly after the driest part of the year, when yield is likely to be at its lowest. This will minimize the possibility of overestimating the yield of your water source. If this is not possible, the drawdown will have to be estimated, preferably with assistance from hydrogeologists familiar with your area.

[5] See Driscoll et al., 1986 for a complete discussion of test pumping procedures and analysis.

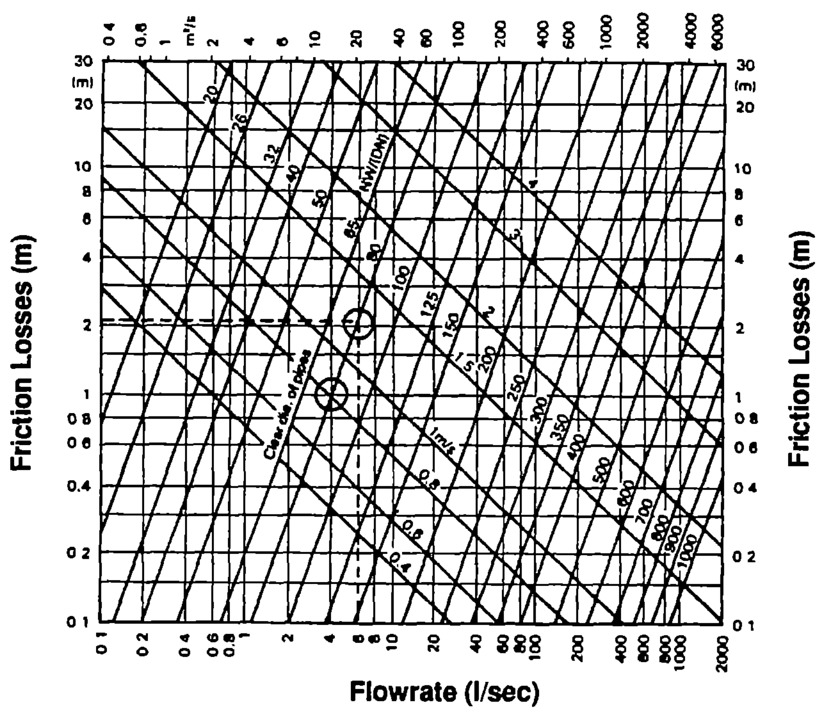
The subsequent selection of pumping equipment should reflect these uncertain conditions (see Chapter 4 on available equipment).

Pipe Friction

Pipe friction loss depends on the flow rate and the length, diameter, and condition of the pipe used. Friction loss increases with age due to encrustation and siltation, especially in small diameter pipes. Potential air traps in siphons can also cause excessive head loss. Friction losses can be calculated using formulas, but they can be determined more easily using graphs or tables. To use such a graph, you must know the type of pipe being used (galvanized iron, smooth plastic, etc.), since friction losses vary with type of pipe and the degree of corrosion or clogging. The graph in Figure 4 can be used to estimate the head loss for galvanized iron or plastic pipes, according to the following example. For example, for an 80 mm galvanized iron pipe 200 meters long at a flowrate of 6 liters/second, the head loss is 2.2 meters per 100 meters of pipe (see dotted line and upper circle on Figure 4). The total head loss is then 2.2 x 2 or 4.4 meters. Other friction losses occur as water moves through valves, bends, and other fittings. These are called minor losses. Additional friction loss tables and figures for a wider range of pipe types, diameters, and minor losses for pipe bends and fittings are given in Appendix B.

Example 2 shows the importance of using pipe that is the right size to save on energy costs by minimizing head losses. One common rule of thumb is that pipes should be sized so that friction losses

Figure 4. A Pipe Friction Loss Chart



Friction losses in metres per 100m for a new pipeline of cast iron

For other types of pipe multiply the friction loss as indicated by the table by the factors given below

New Rolled steel	-	0 8
New plastic	-	0 8
Old rusty cast iron	-	1 25
Pipes with encrustations	-	1 7

Example 2: Pipe Friction (Head) Loss

Find the friction loss in meters of head for a horizontal smooth plastic pipe that is 250 meters long and 80 mm (3 inches) in diameter. The pipe has four 90 degree standard elbows and two open gate valves. Water is being pumped through the pipe at a rate of 4 liters per second (l/sec).

Determine the total equivalent length of the pipe by looking at the Fitting Losses table in Appendix B. For a 90 degree standard elbow, the equivalent length for an 80 mm elbow is 2.3 meters. The equivalent length for an open gate valve is 1.0 meter. Therefore, the total equivalent length for four elbows and two gate valves is:

(2.3 x 4) + (1.0 x 2) = 11.2 meters.

Adding this value to the 250 meter pipe length gives a total equivalent length of 261.2 meters. There are two tools given to calculate friction loss, a chart and a nomograph. First, look at the friction loss chart on the previous page. Along the bottom axis of the chart (flow in liters per second), locate 4 l/sec. Move up to the 80 mm pipe diameter line (the lower small circle on the chart), then across to the left axis titled Friction Losses (in meters per 100 meters of equivalent length), and read 1.0 meter. The total friction loss is then:

(261.2 x 1.0)/100 = 2.6 meters.

Since this chart is for cast (galvanized) iron, multiply the answer by 0.8 (for new plastic) to get 2.1 meters friction loss.

The second way to find the friction loss is to use the nomograph for new plastic pipe in Appendix B, page B-4. Start on the left-most axis (flowrate in l/sec) at 4 l/sec. Draw a line (shown) across the next axis to the right (pipe diameter) at 80 mm, and read 8 m/km on the third axis (friction loss in meters per kilometer of pipe). The total friction loss from the nomograph is then:

(261.2 m x 8 m/km)/1000 m/km = 2.1 meters (same as the chart).

Now, suppose you want to save some money and use cheaper, smaller diameter (say, 50 mm) pipe. Following the same procedure as above, you can calculate the total equivalent length to be:

(1.5 x 4) + (0.7 x 2) + 250 = 257.4 meters.

Again referring to the friction loss chart (or the nomograph), the friction loss is 8.2 x 0.8 (for plastic) = 6.6 meters per hundred meters length. The total friction loss for 257.4 equivalent meters of pipe is then:

(257.4 x 6.6)/100 = 17 meters (confirm this with the nomograph).

This is more than eight times as much friction loss as with the 80 mm pipe, and would increase the power requirement of the pump and engine. The water velocity in this case is about 2 m/sec, well above the recommended limit of 1-1.5 m/sec. Note that for old pipe with encrustations, the friction loss is 1.7 times greater than that shown on the friction loss chart for new galvanized iron pipe.

are less than 10 percent of the total head. Another common rule of thumb is that pipes should be sized so that water velocity in the pipes never exceeds 1.5 m/sec. For the example above, for the 80 mm pipe, the water velocity is 0.87 m/sec, which fits the criterion. For the 50 mm pipe, it is 2.0 m/sec, which does not fit the criterion. In addition to minimizing energy requirements and costs, pipe size selection should also depend on what pipe sizes are available locally.

Velocity

Velocity head is a measure of the energy lost when a moving liquid slows down, such as when it flows from a pipe into a storage tank. For purposes of system design, it is measured as pressure loss in meters of water, calculated using the formula:

$$\text{velocity head (in meters)} = \frac{v^2\ (^m/_{sec})}{2 \times 9.81\ (^m/_{sec^2})} \qquad \textbf{\textit{Formula \#2}}$$

where v is the average velocity of water in the pipe and 9.81 is a constant. For most small-scale pumping applications, the velocity head is small and can be safely ignored. This can be seen from Example 3 below.

Example 3: Velocity Head

Determine the velocity head if water is being pumped at a rate of 10 m^3/h through a 100 mm galvanized iron pipe at sea level under normal atmospheric conditions.

First, find the velocity, v. The cross-sectional area of a 100 mm pipe can be obtained from standard pipe size tables or by using the pipe inner diameter (see Appendix B) and calculating the area from the formula:

$A = \pi \times (\text{diameter})^2 / 4 = 3.14 \times (90.1 \times 10^{-3} m)^2 / 4 = .0064\ m^2$

The velocity equals the flow rate divided by the cross-sectional area, so the velocity in the pipe is 10/.0064, which equals 1568 m/h or about 0.44 m/sec. Using this result in the formula above gives a negligible velocity head of:

$$\text{velocity head (in meters)} = \frac{(0.44\ ^m/_{sec})^2}{2 \times 9.81\ (^m/_{sec^2})} = 0.01\ m$$

Pressure Head

Pressure head is the additional pressure required to pump water into a pressurized tank. This pressure can be given as additional meters or feet of head using the following conversion:

1 psi = 6.89 kPA = 2.306 feet of water = .703 meters of water (psi = pounds per square inch).

It will not often be a factor in water supply systems in developing countries, since pressurized systems are seldom used in rural areas.

Using the approach described here, total pumping head (needed later to determine pumping energy requirements) can be calculated by adding together the values for each of its components:

Total Pumping Head = Static Water Level + Static Discharge Head + Drawdown + Friction Losses + Pressure Head + Velocity Head.

2.3 Water Quality

Water quality certainly is important in determining whether the water source is suitable for human and animal consumption, but it also may have an impact on pumping equipment selection. Water sources should be assessed using the World Health Organization (WHO) drinking water standards[6], particularly for pathogenic organisms such as fecal coliform, as well as turbidity, total dissolved solids, chemical contaminants, (nitrates, nitrites, sulfates, fluorides, manganese, and iron) and heavy metals (arsenic, chromium, cyanide, mercury, and cadmium)[7]. Unpleasant taste (e.g., high iron content) or smell (e.g., hydrogen sulfide) can also make a water source unacceptable. Using unpolluted groundwater is one of the main justifications for pumped water systems. Many people in developing countries have no choice but to use polluted surface water sources due to the lack of access to groundwater (see Photo 1).

For pumping equipment, the following water quality parameters indicate potential corrosion when their levels are[8]:

- pH (hydrogen ion concentration)—less than 7 means that the water is acidic;
- dissolved oxygen (DO)—greater than 2 mg/l;
- total dissolved solids (TDS)—greater than 1,000 mg/l, electrical conductivity can cause electrolytic corrosion;
- hydrogen sulfide (H_2S)—greater than 1 mg/l (which you can smell);
- carbon dioxide (CO_2)—greater than 50 mg/l;
- chlorides (Cl)—greater than 500 mg/l.

Any of the above conditions when combined with any other one (or more) will increase your corrosion problems. High conductance (above 750 micro-ohms), low pH (acidic water below 6.5), and/or high TDS levels (above 500 mg/l) indicate aggressively corrosive water. Acidic water, even with low conductance or low TDS, is also corrosive. Otherwise acceptable water with high TDS levels can de-

6 *International Standards for Drinking Water*, WHO, Geneva, 3rd Revised Edition, 1971.

7 A variety of water treatment options can be used to deal with many of these contaminants. See *Surface Water Treatment for Communities in Developing Countries*, Daniel Okun and Christopher Shultz, WASH Technical Report No. 29, September, 1984.

8 *Groundwater and Wells*, The Johnson Well Company, p.454.

Photo 1.

A woman in Somalia collecting polluted drinking water from the only nearby available water source.

grade equipment simply by an excessive wear, as particles moving over the pump's moving parts wear them down.

Corrosion can be chemical or electrochemical. Chemical corrosion occurs when a contaminant exists in sufficient concentration to cause corrosion over a broad area such as a steel pump casing. Where possible, avoid using groundwater which is acidic, has high concentrations of dissolved gases or solids, or has high temperatures. If you must use corrosive water because it is the only option, then select pumping equipment that can resist the corrosion. Using bronze, stainless steel (e.g., for pump casings), or heavy duty plastic (for drop pipes, or well casings) components will minimize corrosion problems. Minimizing water velocity through well screens and pumps will also help reduce corrosion from sand and dissolved solids.

The following water quality parameters indicate potential encrustation problems when their levels are:

- pH—higher than 7.5;
- carbonate (CO_3) hardness—greater than 300 mg/l;
- iron (Fe)—greater than 0.5 mg/l;
- manganese (Mn)—0.2 mg/l in the presence of high pH.

Hardness is a measure of the mineral content of water, primarily magnesium and calcium. Hardness in the range of 100 milligrams per liter (mg/l) is considered acceptable, although up to 500 mg/l may be acceptable if better quality sources are unavailable. As hardness increases, encrustation and scaling on pipes and pump components is more likely. Over time, this increases pipe friction and decreases the diameter of the pipe, thus affecting the pumping rate and increasing the power requirements. Scale deposition can also decrease well efficiency and may even lead to the loss of a well in extreme cases.

2.4 Water Availability

Water availability is the percentage of time water is available to users during a specified period. This figure is never 100 percent, since every system eventually breaks down or needs to be temporarily taken out of service for maintenance. Availability can almost always be increased, but it can be increasingly expensive to do so above a certain level. Pumped water supplies may be unavailable for three reasons: the mechanical system fails (e.g., the motor stops), the source becomes inaccessible (e.g., the water table drops below the pump intake), or the energy resource fails (e.g., the wind stops, the diesel fuel runs out, or the sun is covered with clouds). A good design practice for water pumping systems is to focus on ensuring an acceptable level of water availability, which depends on:

- equipment reliability;
- variations in water and energy resources; and
- the availability of backup equipment and water sources in the event of a system or source failure.

The reliability of different kinds of pumping equipment and system designs can vary considerably, but reliability usually depends on the quality of equipment and regular maintenance. Usually, better equipment costs more, and there are trade-offs between buying a system that has a high capital cost and low O&M requirements versus low-cost equipment that needs a high level of O&M. Users may have to make compromises if they lack adequate funds for high-quality equipment. However, the most important strategy for preventing problems and minimizing costs is to know the limitations of the water source before you choose a system.

2.4.1 Reliability—Equipment and System Design

Reliability is usually measured as the mean time between failures (MTBF), given in hours of operation. This means that on the average, a component (e.g., pump, engine, or belt), **if properly maintained**, can be expected to fail after the mean time between failures has elapsed. Better (and often more expensive) components or systems have a longer MTBF. Usually, it is very difficult to find this information for different component options, so system designers must rely on recommendations when choosing different types or brands of equipment. However, MTBF does not depend simply on the quality of the parts used. Reliability is also very dependent upon other factors such as the ready availability of spare parts and people with technical skills to maintain and repair equipment.

System designers usually try to pick components with the highest efficiency that they can afford (see Section 4.1 for an explanation of efficiency). Sometimes new equipment with purportedly high efficiency is used in a system. Only later may users discover that the new part functions well for a short time but does not have the expected reliability and fails prematurely. In general, **use proven components that you and local technicians are familiar with or that have proven themselves through long and steady use elsewhere, rather than buying the latest innovation**. Let someone else experiment with new or unfamiliar units. In the long run, proven reliability is much more important in reducing the cost of water delivery than a small percentage difference in operating efficiency. Having said this, always try to use the most efficient system components which have good reputations for reliability.

Good design can greatly increase water availability. For example, the level and the quality of the water in rivers, springs, and wells can fluctuate seasonally and annually. System design should take expected and unexpected changes in the water source into consideration. Strategies for dealing with such changes include:

- mounting borehole pumps well below the lowest expected water level, mounting river pumps on anchored floats with flexible discharge hoses, and using appropriate screens (for both groundwater and surface water pumps) to prevent clogging and subsequent damage to pumps and motors;
- using safety devices—circuit breakers on motors to prevent overloading, overheating cutoff switches to prevent seizing in pumps or motors when water levels drop below the intake, and pressure-relief and backflow valves in discharge lines; and
- designing adequate storage to meet demand during short-term system outages, expected or unexpected—remember, eventually **every** system breaks down.

There are other approaches which can increase water availability. In most common design procedures, components such as engines and pumps are typically oversized to a certain extent. Since pumps require more power to start them turning than to keep them going, motors have to supply higher starting than running torque (see Chapter 5 on diesel engines). For electric motors, this means more amps must be delivered to the motor. Thus, motors and power supplies (e.g., PV arrays, or wind-pump rotors) must be sized large enough or use appropriate electronic controls so they can provide enough power (as much as four times the normal running torque in some cases) to start the system.

Components must also be somewhat oversized oversized to account for gradual degradation of performance and growth in demand over the system's expected lifetime. For example, pipes get clogged due to scaling over time, thereby reducing the diameter through which water can flow. This increases the total pumping head and, for a given power input, reduces the flow rate through the pipe. Similarly, as electrical components wear, voltage losses occur that reduce the output of electric motors. As diesel engines become carbonized and worn with use, they produce less shaft power to drive pump transmissions. These and other types of system performance losses mean you must begin with a slightly larger power source if you expect a certain amount of water delivery five or ten years after the system is installed. Guidelines for component sizing that address these problems are given in Chapters 5 through 8.

The need for preventive maintenance to increase system reliability cannot be overemphasized. Pumps and motors run better (i.e., more efficiently and at a lower cost per unit of water delivered) when they are regularly maintained. Nonetheless, many systems are not properly maintained, for a variety of reasons. Users may not understand the need for regular maintenance, may not know how to do perform the maintenance, or have access to technicians with the knowledge. There may be a shortage of spare parts, or more simply a shortage of money to buy them. Chapter 9 discusses these problems in detail.

Every pumping system will eventually fail. System designers have a responsibility to consider how users will deal with such failures. You must determine how long an outage will be acceptable to users (i.e., how will they get water until the system is put back into operation?), remembering that no system gives water 100 percent of the time. Unless the situation is very unusual, the right spare parts or people with appropriate technical skills will not be on hand at the site to fix a system immediately after a breakdown occurs. Thus, outages often last several days or more before parts and mechanics can be found to fix the problem.

2.4.2 Backup and Hybrid Systems

System design should take into account ways of dealing with maintenance problems. First, you need to have some idea of what problems will be caused by even brief outages. Do people typically store the drinking water needed for several days at their houses, or do they draw water several times a day because they have no off-site (i.e., in their homes or yards) storage? If there is little or no off-site storage, a community storage tank should be big enough to store water for at least one day, and preferably two.

Second, backup systems can be used whenever the primary system fails or is shut down for maintenance. While this almost guarantees that you will always have water (so long as your energy source is sufficient), it also means that the system will be more expensive. Further, people often do not place a high priority on maintaining backup systems. Backup systems must be kept in good operating condition so they are available when needed. Some pumping systems can easily be designed to incorporate backup engines or energy sources. For example, suppose a PV system with a vertical-turbine pump is driven by a pulley on top of the pump shaft. Normally, the pulley is driven by a belt connected to the electric motor. A backup diesel engine could be installed by mounting it so that if the solar system fails, due to equipment failure or simply to a lack of sun, the diesel engine could be used to meet demand until the PV system is working again. Backup systems which are fully integrated into the main system are often called hybrid systems. Similarly, handpumps could serve as backups for diesel, wind, or solar pumping systems, and diesels could back up wind pumps. For protected open wells, a bracket/pulley/rope system could also serve as a backup.

A third solution is to have more than one water supply system (pump and water source). If one system fails or needs to be taken out of service for any reason, the second will still be able to supply some minimum level of service. Of course, this requires the additional expense of digging a second borehole or open well and installing and maintaining a second pumping system.

Any suggested solution for handling system failure must be weighed against the cost of an unexpected outage—if water is unavailable for a certain amount of time, what are the consequences?

- Can enough water be lifted by hand to supply at least drinking water until the pump is fixed?
- Can enough water be trucked in or transported by other means (e.g., donkey carts)? Are the roads passable, what would this cost, and who would pay for it?
- Would people have to travel to or temporarily move nearer another water source until the system is repaired?
- When water is being used for agricultural purposes, what happens if the crop fails?

The costs of the options discussed above or similar emergency-relief measures must be weighed against the cost of a backup system, additional storage, or developing other water sources.

Chapter 3: Energy Demand and Resources

An important aspect of choosing pumping equipment is determining the energy required to pump water and assessing what energy sources could be utilized. This chapter demonstrates the method for calculating energy demand and discusses the characteristics and limitations of a variety of energy resources.

3.1 Hydraulic Energy Demand

Energy is the capacity to do work. For pumping or lifting water, hydraulic energy is the capacity to move a specified volume of water against a certain head. Energy is expressed in joules, horsepower-hours, watt-hours, or (most commonly) in kilowatt hours (kWh). Power is the rate at which work is performed, measured in horsepower or Watts (or kilowatts, kW). One Watt of power used for one hour is one Watt-hour. One Watt used for 1,000 hours is one kWh.

Both terms are important in determining the correct size for pumping equipment. Engines or motors are usually rated in terms of power output (kilowatts or horsepower). The energy requirement indicates how long that power output must be sustained, typically over a day. Power in watts is:

$$Power\ (P_W) = 9.81 \times H \times Q$$

Formula #3

where P_W = power (Watts)

H = total pumping head (meters)

Q = volume of water pumped (liters per second, l/sec)

The hydraulic energy required to lift a certain volume of water is given by the following equation:

$$E_h = \frac{\rho_W \times g \times Q_D \times H}{(3.6 \times 10^6) \times \eta}$$

Formula #4

where E_h = hydraulic energy in kilowatt-hours (kWh)

ρ_W = density of water (1,000 kg/m^3)

g = gravitational constant (9.81 m/s^2)

η = efficiency of pump (in percent–see below)

Q_D = volume of water pumped (m^3/day)

H = total pumping head (meters)

Substituting the given constants (9.81, 1,000, and 3.6), the equation simplifies to

$$E_h = \frac{(.00273 \times Q_D \times H)}{\eta} \qquad \textit{Formula \#5}$$

The theoretical amount of hydraulic energy E_h required to pump a given amount of water is directly proportional to the head and the daily water demand. Thus, strictly in terms of hydraulic energy requirements, pumping 20 m^3/day from a head of 50 meters is the same as pumping 50 m^3/day through 20 meters of head. Taken together, the head and daily water requirement determine the energy demand. However, this convenient simplification does not take into account differences in friction losses when water is pumped through different lengths and diameters of pipe.

The hydraulic energy requirement calculated using Formula #5 above is significantly less than the actual energy needed to move water because of inefficiencies in system components (pumps and engines). For example, the energy efficiency of converting:

- diesel fuel to pumped water ranges from 5 to 20 percent;
- solar irradiation to pumped water is 3 to 5 percent;
- wind energy to pumped water is on the order of 4 to 8 percent; and
- foodstuffs to water pumped by humans is anywhere from 5 to 10 percent.

When comparing different types of pumping systems, these efficiencies by themselves do not determine the best choice. Other system characteristics—such as cost, ease of maintenance, and capacity—are also important. However, for a specific type of system (e.g., wind pumps), efficiency is an important consideration in choosing between competing wind systems. The **most** important energy consideration is whether the available energy resource is sufficient to meet the pumping requirement.

Each component of a mechanical system (e.g., motor, pump, transmission, etc.) has its own efficiency, which is the ratio of the power out to the power in. Electric motor efficiencies are usually about 65-90 percent (higher for larger sizes), and pump efficiencies range between 40-75 percent, depending on how well the pump is matched to its load (i.e., the head and flow--see Chapter 4). For convenience, we will refer to the combined pump, motor, and transmission (the entire subsystem) efficiency as the "subsystem efficiency." If pumps are normally purchased in an integral unit with the motor (such as a submersible pump), people commonly refer to the combined pump and motor efficiency as the pump or subsystem efficiency. For example, if the motor efficiency is 80 percent, the pump (by itself) efficiency 70 percent, and the transmission efficiency 75 percent, the subsystem efficiency is the product of each individual component's efficiency.

Subsystem efficiency = motor efficiency x pump efficiency x transmission efficiency ***Formula #6***

Accordingly, the subsystem efficiency in this case is 0.80 x 0.70 x 0.75 = 42 percent.

Example 4: Hydraulic Energy Requirement

A. What is the theoretical hydraulic energy required to pump 20 m^3/day against 75 meters of head?

From Formula #5,

$$E_h\ (in\ kWh) = \frac{.00273 \times 20\ m^3/_{day} \times 75\ m}{\eta}$$

$$E_h = \frac{4.1\ kWh}{\eta}$$

B. If the pump (only) efficiency is 60 percent, how much energy must actually be provided by an engine?

$$E_h = 4.1\ kWh/.60 = 6.8\ kWh$$

C. If water is pumped over a six-hour period, what is the required mechanical power output from the engine?

power = energy/time

6.8 kWh/6 hours = 1.1 kW

Note that you can meet the 20 m^3/day requirement by pumping 20 m^3/h for one hour, or by pumping 20 m^3/day in 6 hours at 3.3 m^3/h. The choice of flow rate does not change the energy requirement per se (although if you use the same size pipe, your friction losses will increase greatly), but does determine the power output requirement for the pumping device. Diesel engines and PV modules, in particular, are rated in units of power. This fact is important in later sections on engine selection.

3.2 Energy Resources

Traditional energy resources for delivering water include gravity, hand lifting, and wind energy. Over the last 70 years petrochemical fuels and electricity have been utilized. Over the last ten years, solar energy has been directly converted to electricity to run specially modified pump/motor systems. One basic aspect of the pump selection process is evaluating the availability of and potential for using different energy resources. In nearly all cases, if water can be delivered by gravity, it is likely to be the most reliable and cost-effective system. However, if the capital cost of a long pipeline or channels is high, or water quality is not suitable for the intended use, or (more commonly) you simply need the water uphill from the available source, pumping systems must be considered. The following sections provide guidelines for determining the resource information needed to make a preliminary evaluation of pumping equipment options.

3.2.1 Hand Lifting and Carrying

Other than gravity flow, lifting and carrying water by hand is the oldest method of moving it from a source to a destination. Many hand-operated delivery systems have been used around the world[1]. The major limitations of hand lifting are the sustainable energy output of humans and the relatively small water delivery rate. Hand lifting can include every option from a rope and bucket to modern, high-efficiency handpumps. Remember that under certain circumstances, the bucket and rope method of drawing water may be perfectly appropriate for some sites. Do not dismiss the no-pump option before considering it thoroughly.

A human's maximum continuous power output for short periods is about 100 watts (0.1 kW). This cannot be sustained over the course of a day. For an average adult male, the energy output over a day is about 0.2 to 0.25 kWh. Assuming a pump that is 70 percent efficient, this would amount to pumping only 3.2 m^3/day for a head of 20 meters (from Formula 5). With multiple pumpers, which would usually be the case, 0.75 to 1.0 kWh (or about 13 m^3 of water) could be produced over a day.

These conditions severely limit the amount of water that can be delivered using hand-operated pumps. However, if the energy requirement is small because the water requirement and/or head are very low, and a willing labor force is available, human-powered systems should seriously be considered as a low-cost, low-maintenance option. The main question would be whether or not daily water demand could be met with handpumps.

3.2.2 Petrochemical Fuel and Electrical Energy

Petrochemical energy sources—diesel fuel, gasoline, and kerosene—are widely available in nearly every country in the world (there are, of course, periodic shortages, price fluctuations, and fuel delivery problems). Nevertheless, it is important to consider system operating costs, as well as whether they are and will continue to be reliably available in the quantities needed to meet daily energy requirements. Since gasoline and kerosene engines are not nearly so common as diesel engines for pumping water and are generally more expensive for most small-scale water pumping needs, they will not be discussed further here, although the same design and cost estimation approach could be applied.

Fuel availability and costs depend on many factors, including:

- supply at the national level;
- reliability of national and regional distribution systems—public and private, formal and informal;
- priority allocation schemes—fuel may be allocated or diverted to government projects, important industies, or politically well-connected regions or individuals;
- local variations in demand—an unexpectedly high periodic demand sometimes depletes local fuel supplies; and

[1] See particularly *Water Lifting Devices*, Fraenkel, P., 1986.

- other market distortions, such as fixed government prices applied in one area, when black marketing brings much higher prices in another area.

The suitability of electrically operated pumps depends on their proximity to the electricity grid and the reliability of service. Since grid power is uncommon in many rural areas of developing countries, grid-electric pumps will not be considered further here. However, in most cases where reliable grid power is available at a site, electric pumps are the preferred system for technical and cost reasons. Electric motor/pump systems can be analyzed using the same principles given in the solar electric pump section.

The appropriateness of a diesel, electrical, or any other pumping system is based in part on past energy availability, its likely availability in the future, and the degree of system reliability that is required. When considering diesel or electric pumping systems, you should determine whether past problems with energy availability and fluctuations in fuel costs are great enough to warrant considering other types of systems.

Diesel engines are available in essentially any rated power output between 2.0 kW and 20 megawatts (MW), so finding equipment with the right capacity is generally not a problem except for very small outputs (less than 2.0 kW). A full discussion of factors affecting diesel fuel consumption rates and methods for calculating consumption and power output are given in Chapter 5.

3.2.3 Solar Radiation

The performance of a solar pumping system is proportional to the solar energy falling on the PV array (the set of solar modules that produce electricity). Solar energy (or irradiation) is measured with a pyranometer, which gives readings in power per unit of horizontal area in Watts or Joules per square meter per second (W/m^2 or J/m^2sec). These power measurements are integrated over time (usually a day) to give energy in kilowatt hours per square meter per day (kWh/m^2day) or megajoules per square meter per day (MJ/m^2day). The conversion ratio is 1 kWh/m^2day to 3.6 MJ/m^2day.

As an example, a good solar radiation day in a semi-arid climate at less than 25 degrees latitude is about 6 kWh/m^2day (or 21.6 MJ/m^2day). One peak sunlight hour is defined as 1 kWh/m^2. The literature of some PV pump manufacturers refers to the number of peak sunlight hours as a way of quickly estimating local solar radiation levels. Remember that irradiation can vary considerably over a day, month, or year, depending on local weather conditions and latitude. In addition, annual averages can vary significantly from one year to the next.

Solar and wind pump sizing is based on the concept of the design month, which was mentioned in Chapter 2. During the design month, the ratio of available energy (monthly average solar irradiation or wind speed) to the hydraulic energy requirement is at its lowest (see Example 14 in Section 7.3.2). In general, solar pumping systems are not cost-effective unless irradiation during the design month is greater than about 5 kWh/m^2day. Again, this guideline is somewhat flexible, depending on site-specific costs and operating constraints. World-wide maps of solar radiation data do exist[2], but those data are not precise enough to be used as the basis for a site-specific system design.

[2] See *Solar Water Pumping Handbook*, Kenna and Gillett, IT Publications, 1985.

To assess PV pump suitability and performance the following information is needed, at a minimum:

- the average daily solar energy available at the site during each month of the year; and
- the average daily temperature for each month (because PV array output decreases as the operating temperature increases).

Normally, wind or solar data are not available for the pump site, but they may be available for some other site nearby. As is true of wind speed, solar irradiation is partially dependent on the terrain and microclimate. However, solar irradiation is generally not so variable as wind speed, nor is the amount of available solar energy so sensitive to the amount of irradiation as wind energy is to wind speed. Hence the effects of differences between design site data and data recorded at nearby meteorological sites are not as pronounced for solar as for wind-energy systems. Thus, solar irradiation data from pyranometer sites that are as far away as several hundred kilometers may be acceptable. This is fortunate as the worldwide network of stations measuring solar irradiation is much more limited than that for wind measurements. Variations in the amount of irradiation depend on how different the microclimate at the proposed pumping location is from that at the recording site.

The electrical energy produced by a PV array depends not only on the operating temperature and incident solar irradiation, but also on the size of the array and the angle at which it is tilted up from the ground. The more nearly perpendicular the array is relative to the sun's rays, the more electrical energy will be produced. Details on solar pump sizing, based on the energy-resource information discussed here, are provided in Chapter 6.

3.2.4 Wind Regimes

To evaluate the potential use of wind as an energy source, measurements or estimates must be made of local wind speeds over the course of a year. The energy output of a wind pump is directly proportional to power available in the wind over time. The water output for a particular windmill is proportional to the energy available, which depends on wind speed and rotor diameter, and inversely proportional to the total head.

The wind pattern or regime can be characterized approximately by an average speed (measured in m/sec or miles per hour [mph] at a given height) over a given period, usually a month. Generally, windmills should not be considered if a site's average wind speed during the month with lowest speeds is less than 3.5 m/sec or the total pumping head is over 60 meters. However, a combination of many site and cost factors finally determines the lowest average wind speed at which windmills are a practical alternative.

Most people will not want to measure the wind at the proposed site for a year before deciding whether to purchase a system; however, windspeed data are occasionally available for nearby sites as hourly averages, and more often as daily or monthly averages. To assess the location's suitability for windmills and to estimate performance, monthly average wind speeds near the site are required for a period of at least one year. If available, recorded data for longer periods are very useful in assessing whether that year of data is an accurate representation of long-term wind speeds at the site. The more detailed the windspeed data used in system design, the more accurate the prediction of the performance of particular windmills.

At a minimum the following information is needed about the wind regime to assess windmill performance:

- monthly average wind speeds over the course of one year (used to determine the months with low wind speeds and to identify the design month);
- the location and height of the recording instruments used, since wind speed varies with height; and
- a description of the terrain where the wind speeds were recorded, and the topography between that location and the proposed pump site (trees, hills, and other features can dramatically affect wind speeds).

A discussion of the calculations and corrections required to choose a windmill and predict its performance is provided in Chapter 7.

3.2.5 Energy Resource Data

It is important that information on energy resources be as complete as possible. In most cases, this means gathering data locally. Site visits are highly recommended for recording important resource parameters and assessing exposure and terrain conditions relevant to possible wind or solar energy use. In addition to data collection at the site, other sources of information on energy resources include:

- the national department of meteorological services;
- airports and departments of civil aviation;
- university or polytechnic science departments;
- the country's department of agriculture; and
- agencies responsible for energy, mines, and/or dams.

Additional sources of information concerning the energy resources discussed in this section are briefly described in the annotated bibliography (Appendix A). Local estimates of variability in wind or solar resources may also be helpful, especially if little or no other data are available. Talk with local people about their perceptions of area weather conditions. Their perceptions may be particularly useful in assessing daily variations in resource levels, such as periods of calm or cloud cover. While such information may not always be accurate, remember that most villagers have been living in the same place for a long time and, thus, may be able to verify data from distant weather stations.

Chapter 4: Available Equipment—Pumps and Drivers

Pumps are selected based on the required flow rate and head. The engine is then chosen to match the pump's power requirements. This chapter discusses the basic operating characteristics of pumps (i.e., pump curves), the different kinds of water pumps available, and selecting the pump with suitable operating characteristics to meet a particular need. As you might expect, certain types of pumps are appropriate for certain applications—specific head, flow rate, and water quality conditions. The advantages and disadvantages of various kinds of pumps and their suitability for use with different types of engines (referred to more generally as drivers or prime movers) are also covered in this chapter. The final section of this chapter describes the advantages, disadvantages, and most appropriate applications for the four types of pump drivers covered in this manual—diesel, solar, wind, and human power.

4.1 Pump Characteristics

The most important technical characteristic for predicting pump performance is the pump curve. Pump curves (see Figure 5 for two examples) show a pump's operating range in terms of total head, flow rate, and efficiency. While each pump model has a unique pump curve, different types of pumps have characteristic curves. Figure 5a shows typical pump curves for a vertical turbine pump and Figure 5b for a positive displacement pump operating at a variety of different speeds (note that the axes are reversed in the two figures). These pump performance curves also include power consumption and efficiency curves. In Figure 5a, the curve labeled "H(Q)" is the head/flow curve, the curve labeled "η%" is efficiency and the curve labeled "P" is power. Efficiency curves can be used to refine system design by helping you to choose a pump that operates most efficiently for your system's total head. The "operating point" or "design point" is the point on the pump curve which matched the total pumping head for your site. If efficiency curves are not available, you can calculate them given the pumping head, flow rate, and power requirement, using the energy requirement calculation presented in the previous section. Example 5 explains how to use a pump curve to find flowrate and efficiency when you know total pumping head.

The efficiency of the pumping system and its components can have a considerable effect on recurrent costs. A system with lower efficiency consumes more energy pumping a given amount of water than a similar system with higher efficiency. However, there are often trade-offs between higher efficiency and lower capital costs. Overall efficiency depends on each system component (e.g., pump, engine, and transmission) and how well the system was designed to match the physical characteristics of the water source. Often, more efficient components cost more, just as longer-lasting equipment costs more (this is particularly true of diesel engines). The system designer's task is to pick the most efficient and durable, well-matched components for the most affordable cost.

To determine the required flow rate and head, you must know the characteristics of your water source, as discussed in Chapter 2. Generally, it is recommended that the average flow rate, in cubic meters per hour (m^3/h) or liters per second (l/sec), should be no more than about 70 percent of the maximum sustainable yield of the well or other water source. This will help minimize the possibility of over-pumping the source and will reduce excessive drawdown, thus minimizing the head and en-

Figure 5. Pump Performance Curves

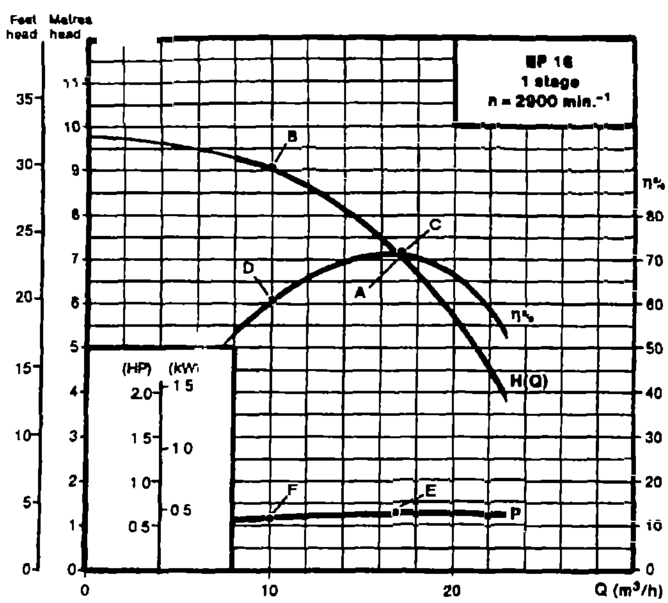


Figure 5a. Centrifugal Vertical Turbine Pump (Grundfos)

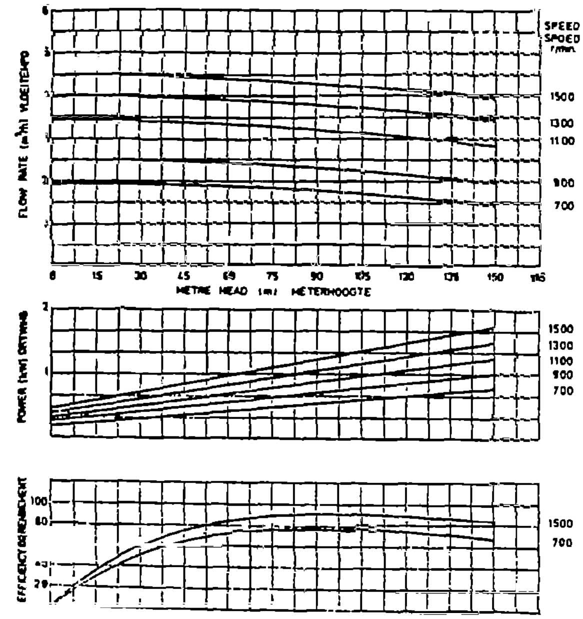


Figure 5b. Rotary Positive Displacement Pump (Mono)

Example 5: Pump Performance at a Given Head

What is the flow rate of the pump in Figure 5a when the total system head is 7 meters? What would it be if the head were increased to 9 meters? What is the efficiency and power requirement at each point?

A. From Figure 5a, the operating point (Point A on the graph) of the BP-16 pump is 17 m^3/h at a head of 7 meters.

B. Again from Figure 5a, if a ground tank added 2 meters to total system head (making it 9 meters), the pump output would be reduced to about 10 m^3/h (Point B on the graph). When pumping head is increased (by pumping up to a tank, for example), the volume of water output decreases, since it takes more energy to pump to the additional height of the storage tank.

C. At 7 meters head the pump delivers 17 m^3/h. To find efficiency, first locate the operating point (C). Then move up or down to intersect the efficiency curve (here they cross at the same point). Read the value of the efficiency curve at that flow rate to get about 71 percent (reading off the right side scale of the graph to Point C). At 9 meters head and 10 m^3/h, from the operating point at B move down to intersect the efficiency curve at Point D. Then move to the right axis to read 60%. To find power consumption, move directly down from the operating points (C and B) to intersect the power curve, then read the kW scale in the lower left corner of the graph. At 7m head, the pump draws about 0.5 kW (Point E). At 9 m head it draws about 0.45 kW (Point F). In both cases, power consumption (shown in the bottom curve) is just below 0.5 kW.

ergy requirement. Below 70 percent of the well's yield, the flow rate is determined by the water demand in cubic meters per day (m^3/day) and number of hours you want to operate the system.

The flow rate for diesel pumps is essentially constant because of the engine's constant operating speed. In most cases, you would simply choose the flow rate (below the 70 percent sustainable yield limit) needed to meet your water requirement if the pump is run six to eight hours per day. Flow rates for handpumps generally do not approach the limit on yield of the water source, but are dependent on the speed at which the pump is operated manually. Because of the cubic relationship between flow rate and wind speed (see Chapter 7), pumping rates for windmills can be very high during gusts. As a general rule, do not design the output of a wind system to be more than one-third of the source's maximum daily sustainable yield. For example, if the source yield is 3 m^3/h (or 24 x 3 = 72 m^3/day), a windmill should be sized to pump routinely no more than 1/3 of the daily 72 m^3 yield, or 24 m^3/day.

For solar pumping systems without batteries, output varies over the day (see Figure 15, Chapter 6), with the maximum generally occurring around noon when the sun is highest in the sky. The average daily flow rate (average daily output divided by number of hours of operation--usually about 8-10 hours) should be no more than about 70 percent of the water source's maximum sustainable yield. For both the solar and wind cases, using these design limits will help prevent over-pumping of the water source (and consequently large drawdown) during periods when the energy resource is strong.

On electric-submersible pump sets the pump and its motor are integrated into one unit. Pump performance graphs for these pumps often show multiple head and flow curves and efficiencies for different motor voltages (see the solar pump curves in Figure 6), or for different motors with regular alternating current (AC) submersible pumps. For example, at point A in Figure 6, the pump will deliver 0.95 l/sec at 25 m head at an efficiency of 49 percent, when operating at 45 volts. For PV pumps, an additional parameter that specifies system performance is the level of solar radiation in the plane of the array. For a particular radiation level, a point on the curve indicates how much water the pump will deliver for a given head. An example of these curves is given in Figure 7. For example, at Point A, at a radiation level of 6.5 kWh/m^2-day (a typical bright, sunny day in Sudan), the pump will deliver 22 m^3/day at 50 m head.

Various types of pumps have performance curves with very different shapes. Figure 8 shows typical curves for centrifugal and reciprocating pumps. Understanding how these curves apply to a particular situation will help you to choose an appropriate type of pump. For example, if a well has a water level that is seasonally variable (i.e., it depends on rainwater for recharge), there are advantages to choosing a reciprocating pump over a centrifugal pump. If the centrifugal pump operates at the middle (most efficient) point of its performance curve during the wet season, when the water level drops off in dry months the total pumping head will increase, thus reducing efficiency and output. However, output for a reciprocating pump is nearly independent of the head. If the water level drops, the system will continue to pump nearly the same amount (as long as the water does not drop below the level of the pump), but at a higher power consumption than if the water level were constant.

Figure 6

Pump Performance Curves: Submersible Centrifugal Pump at Variable Voltage

(Jacuzzi Manufacturing Literature)

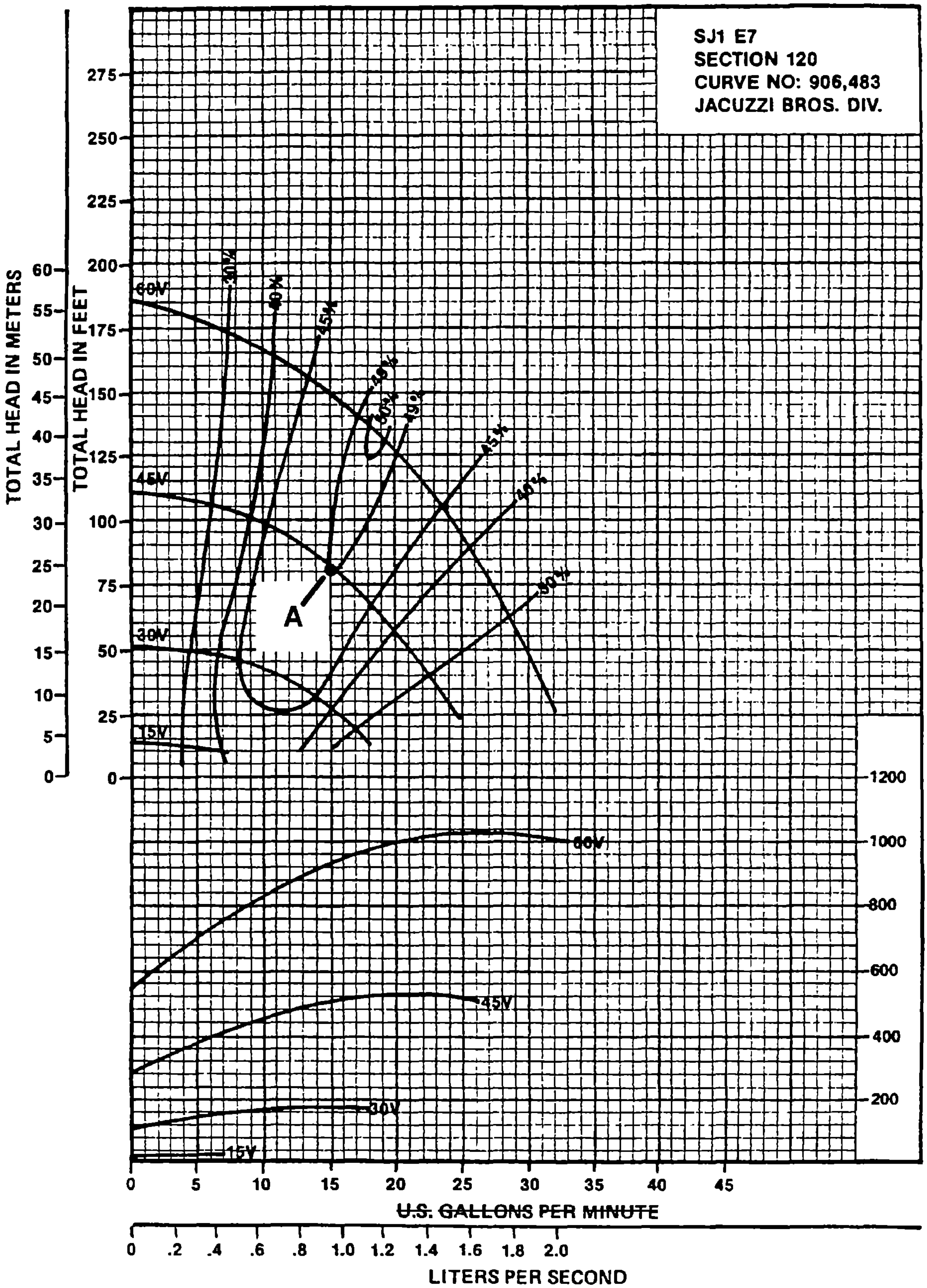


Figure 7

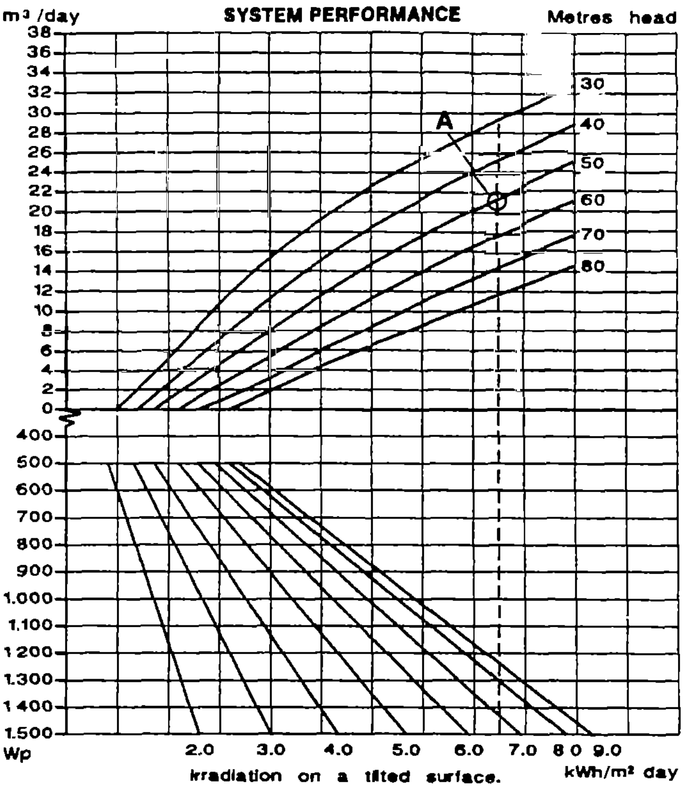
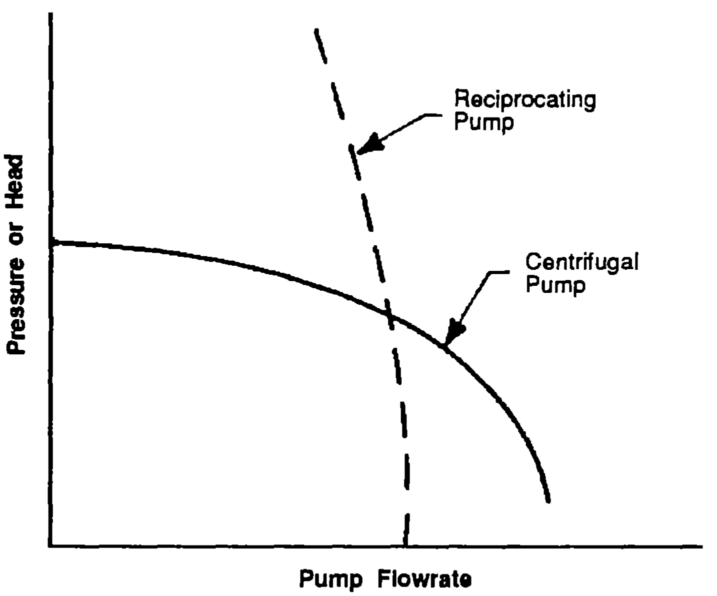


Figure 8



Centrifugal vs. Reciprocating Pump Pressure and Flowrate Characteristics

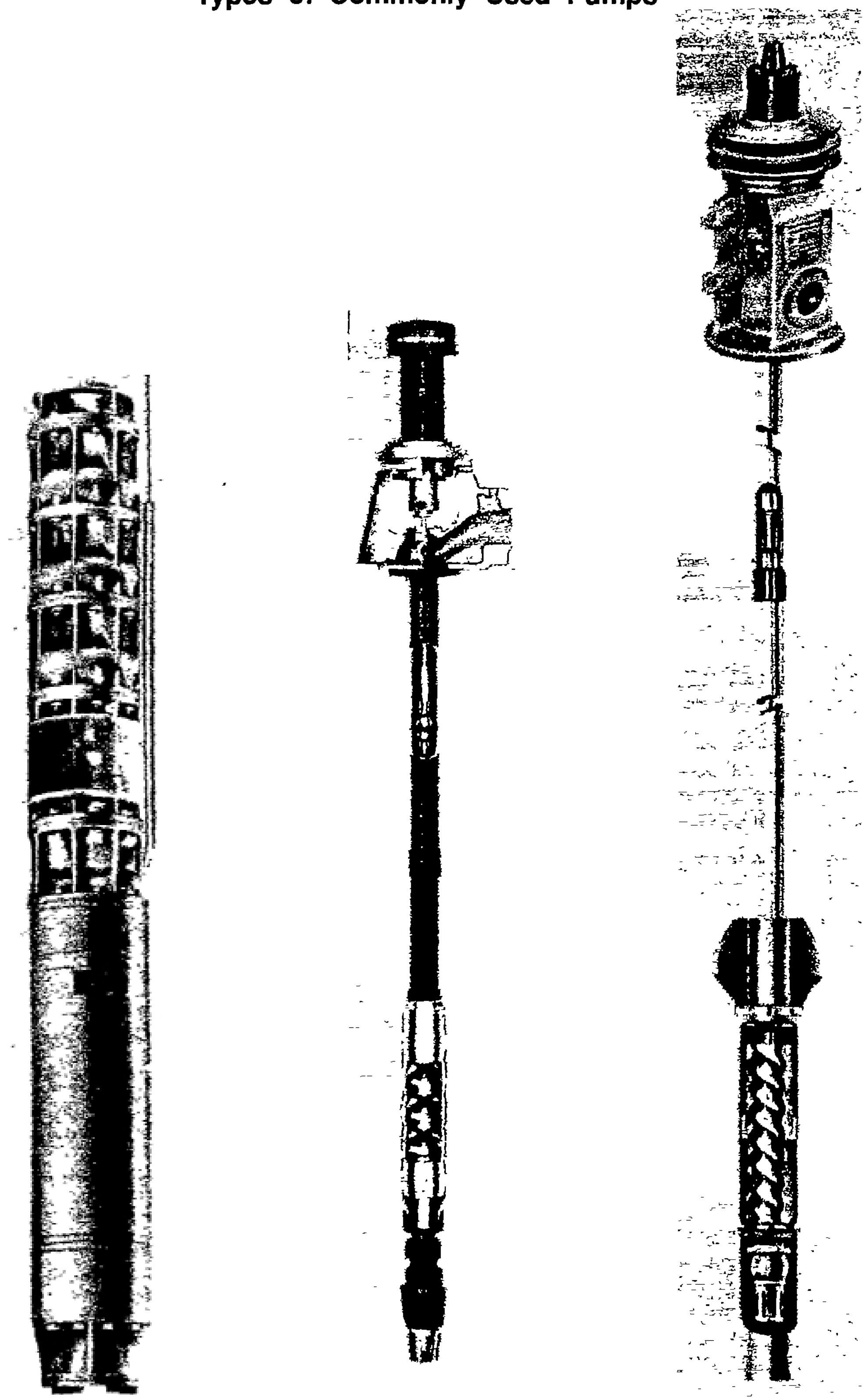
4.2 Advantages and Disadvantages of Different Pumps

Of the many types of pumps are available, seven are commonly used in diesel, solar, wind, and hand-pumping systems. Table 2 gives a brief description of their typical uses, advantages, and disadvantages. Illustrations of common designs for these pump types are shown in Figure 9.

Table 2

Pump	Use	Advantages	Disadvantages
Self-Priming Centrifugal	Surface-mounted motor and pump for high-volume, low-head applications, commonly used for irrigating from a river	Ease of installation and access, low starting torque, wide range of capabilities	Limited 5-meter suction head, relatively inefficient compared to centrifugals that have flooded inlets (such as submersible and shaft-driven units); output greatly affected by variations in head
Submersible Centrifugal	Down-hole, medium-volume, high-head, integrated motor/pump unit	Motor is directly coupled to impellers, easily cooled because submersed, multi-stage to accommodate a wide range of heads; straightness of well not critical; no noise; no pumphouse necessary	Potential problems with submerged spliced electrical cables, sandy or highly saline water causes rapid degradation (water quality affects replacement interval for pump and motor since these are submersed), high capital cost; expensive to repair (pump set requires removing unit from well); requires electricity (cannot use other drivers), needs voltage fluctuation protection
Shaft-Driven Centrifugal Vertical (or Deep Well) Turbine	Down-hole, medium-volume, medium-head pump driven by rotary shaft	Surface-mounted motor offers ease of maintenance, self-priming; wide range of capacities available; good sand/silt tolerance	Shaft losses reduce efficiency compared to submersibles, shaft and borehole alignment are critical to proper operation; installation is difficult; output affected by variations in head, difficult to maintain (pump must be pulled for service)
Jet	Medium-head, medium-flow, down-hole pump and surface-mounted motor	Low equipment and maintenance costs; can be used beyond suction limit; very reliable, easy access to motor and pump for maintenance; low starting torque, least expensive intermediate-head pump, adaptable to very small wells (50 mm)	Relatively inefficient compared to other types of pumps
Positive-Displacement Reciprocating-Piston (Jack)	High-head, low-flow, down-hole piston and cylinder, driven by sucker rod from surface, most commonly used with windmills	Can pump low flows against very high heads; output is fairly independent of head; simple design, easy to repair, efficiency little affected by changes in head	Maintenance requires periodic replacement of leathers and cylinder; requires correct alignment, more expensive than centrifugals of same size, relatively inefficient as leathers degrade; pulsing flow; in PV systems (see Chapter 6) requires batteries or power-conditioning units (PCUs) for high starting current
Positive-Displacement Rotary	Medium- to high-head, medium-flow, Mono or Moyno pumps	Generally very robust; output fairly independent of head, simple construction; self-priming; good efficiency over wide range of heads except for under 20 meters, no back-flow valve required, speed of operation can be adjusted to fit conditions without significant loss of efficiency	Sand or very hard water can cause premature degradation of rubber stators; requires gearing; can overload motors if downstream valves are inadvertently closed; installation is difficult. Although newly-developed nitrile stators have lower starting torque, in PV or wind systems standard units require battery or PCU to supply high starting torque
Diaphragm	Flow produced by flexing diaphragm that is generally used for low-head, low-flow applications	Few moving parts; low internal friction; tolerant of sand or other particulates	Low capacity, not appropriate for deep wells; constant flexing causes diaphragm wear, fairly uncommon type of pump

Figure 9.
Types of Commonly Used Pumps

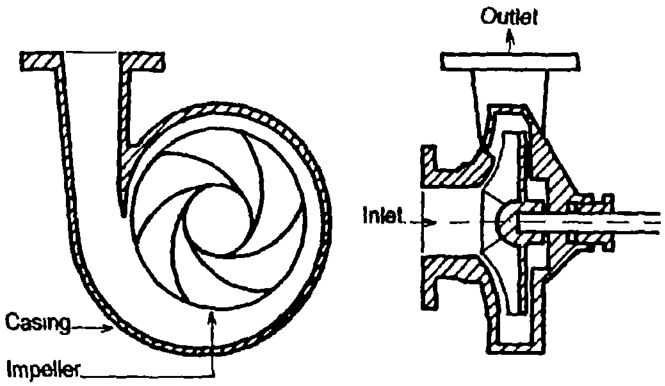


Submersible Centrifugal (Grundfos)

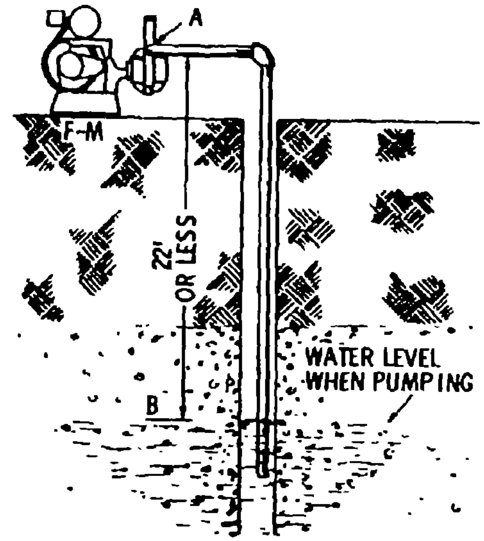
Shaft-Driven Centrifugal (Grundfos)

Positive Displacement Rotary (Mono Pump)

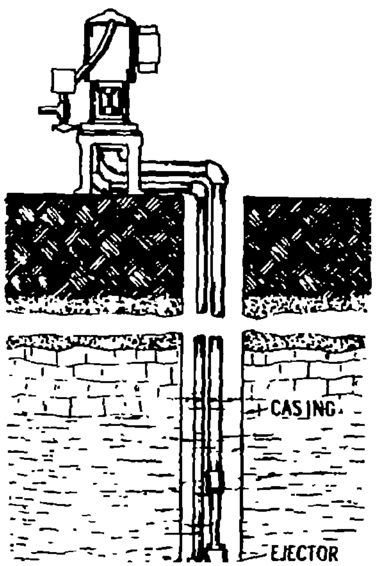
Figure 9 (continued)



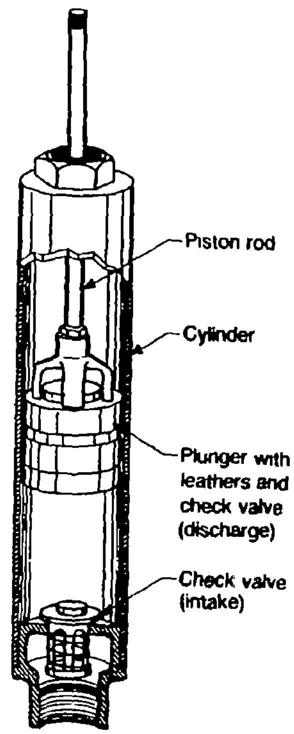
Self-priming Centrifugal (Hofkes and Visscher 1986)



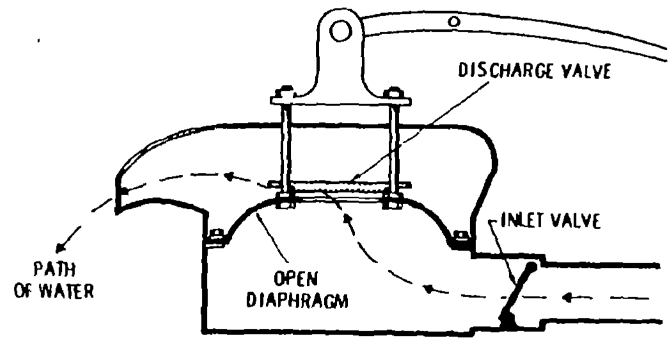
Typical Self-priming Centrifugal Installation
(Stewart 1982)



Jet (Stewart 1982)



Positive Displacement
Reciprocating Piston (Driscoll 1986)



Diaphragm (Stewart 1982)

The comments here concern commonly used, commercially available, small-scale pumps (i.e., less than 10 kW). The first three are all centrifugal pumps—they all have a low starting torque and their output and efficiency are very dependent on the operating head.

4.3 Pump Selection Considerations

There are several other factors affecting pump selection which, although difficult to quantify, need careful consideration. These include:

- reliability (often a direct function of the complexity of the design);
- frequency and complexity of maintenance requirements and technical skill levels, or additional training needed to perform maintenance tasks;
- degree of use in your area—if a pump is commonly used, local mechanics are probably familiar with its operation, and spare parts are likely to be readily available; and
- potential for standardization of equipment, with the goal of minimizing spare parts inventories and technical training requirements.

Pumps are application-specific to an extent. For example, handpumps clearly have a very limited application for irrigation. However, various types of hand-operated pumps—for instance, rower pumps, standard reciprocating-piston handpumps (e.g., Dempster or India Mark II), and rotary pumps (Mono)—have been used in several countries for micro-irrigation. Generally, river-pumping applications for water supply or small-scale irrigation systems, which normally require high flows at low heads, use centrifugal pumps because of their high capacity, reliability, and ease of maintenance. For applications requiring a high capacity system, surface-mounted centrifugals are employed for low heads, and vertical turbine centrifugals for deeper wells—both are relatively inexpensive and their motors are easily serviced. To provide drinking water from wells, submersibles or positive displacement pumps are a more likely choice. They are usually more efficient, but their capacity is lower.

These are just some examples of pump applications. Table 3 shows practical head and output limits with various power sources for these and several other pumps. This information is shown graphically in Figure 10. To a large extent, the choice of a pump will be dictated by constraints associated with the water source—requirements for the head and flow rate, well casing diameter (if pre-existing) and the variability of the source. In many cases, any one of several different pump types will perform adequately. The important point is to choose a system that will operate efficiently and reliably under the design conditions at your site.

The process of choosing the right pump for your particular application is as follows:

- Choose a pump type that is appropriate for your particular application, based on head and flow ranges, and the advantages and disadvantages given in the previous section and Table 2.
- Based on an informal survey of the local availability of various makes (manufacturers) and models of the type of pump you have chosen, select three or four models which best fit the site conditions (meaning that the head/flow operating point you have determined is

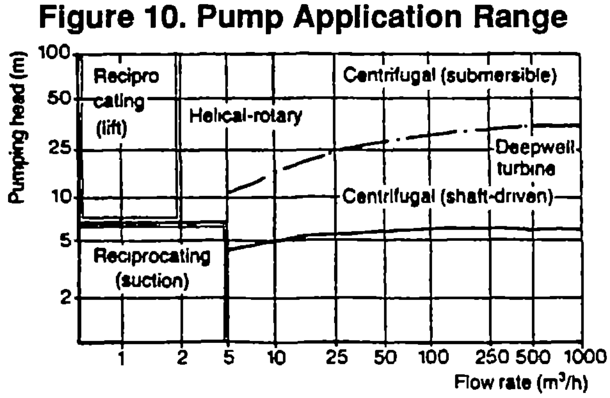
Table 3

(adapted from Hofkes and Visscher 1986, p. 61)

Type of Pump	Pump Subcategory	Practical Depth Range (m)	Capacity Range (m^3/hr)	Common Power Source
Centrifugal Pumps	Single Stage Surface Mounted	15-20	Variable	Diesel (direct-drive)* Diesel (electric)** Grid electric Solar electric
	Multi-stage Submersible	50-500	Variable	Grid electric Diesel (electric) Solar electric
	Shaft-Driven	15-80	Variable	Grid electric Diesel (direct-drive) Solar electric Wind
Jet	Shallow Well	up to 7	1-6	Grid electric Diesel (electric) Solar electric
	Deep Well	20-60	1-3	Grid electric Diesel (electric) Solar electric
Reciprocating Piston	Shallow Well (suction)	up to 7	2-3	Human Wind
	Deep Well	15-100	2-6	Diesel (direct-drive) Human Wind Solar electric
Rotary Positive Displacement		30-150	1-100	Diesel (direct-drive) Human Solar electric Wind (experimental) animals (experimental)
Diaphragm		5-30	1-3	Human Wind (experimental)

* Power sources are listed in the order of most-common to least-common
**i e , a diesel engine driving a generator to produce electricity to run a pump's motor

Figure 10. Pump Application Range



approximately in the middle of their pump curves). Make sure that you use the right pump curve for pump speed[1], operating voltage (for electric submersibles), etc.

- If possible, talk to several people who have used the pumps to get their opinions on reliability, ease of installation and maintenance, availability of spare parts, and cost of repair;
- Pick the model which has the best combination of high efficiency, low cost, reputation for reliability and ease of maintenance (this may well be a compromise solution).

4.4 Advantages and Disadvantages of the Drivers Covered in This Manual

As shown in Table 3, certain drivers are suitable for certain types of pumps. This section discusses qualitative differences between drivers and, where appropriate, the pumps they are best suited for.

4.4.1 Diesel Systems

Diesel engines are the standard prime mover in most of the developing world (see Chapter 5). They can be used to drive nearly any type of pump, either directly or through an electric generator. Diesel engines are normally characterized by:

- low capital costs, but relatively high recurrent costs for O&M;
- local familiarity with O&M due to existing infrastructural support networks (varying widely in quality) of trained mechanics and spare parts suppliers (this can vary widely from country to country, and even by specific area within a country);
- fuel availability that can be highly variable and affected by seasonally dependent transportation networks;
- fuel costs that often vary seasonally but are generally increasing in rural areas (despite current decreases or stability in world oil prices);
- on-demand pumping capability, as opposed to wind or solar pumps, which are dependent on the availability of variable renewable energy resources;
- equipment that is commonly available for essentially unlimited capacity in terms of head and flow rate, except for small loads (less than 2 kW);
- relative portability of smaller units, which are generally high-speed (except for the older Lister-type engines, which are cast iron and quite heavy); and
- the need for an attendant during operation.

[1] In general, the slower the operating speed of the pump, the lower the maintenance required. High speed pumps deliver more water, but their bearings and other moving parts wear out much faster than slow speed pumps.

4.4.2 Solar PV Systems

Solar pumping systems typically consist of a PV array (i.e., the power source), power-conditioning equipment, an electric motor, and a pump (see Chapter 6). They are usually characterized by:

- relatively high capital equipment costs and low recurrent costs for operation (since there is no fuel requirement), maintenance, and repairs;
- limited capacity for commercially available equipment—up to 2.2 kW peak power input, which can provide about 40 m^3/day from 25 meters of head (although this can vary widely from country to country and even from one area to another within a country)[2];
- no on-demand pumping capability, though water storage tanks or batteries can be used to minimize this limitation;
- low portability for most installations because of the PV array—some smaller units of less than about 500 watts peak can be mounted on trailers for portability;
- electromechanical controls, which allow for unattended operation;
- susceptibility to vandalism—stones can easily break the glazing on PV modules; and
- very high reliability for the power supply (i.e., the array), but not always for the energy supply (the sun).

4.4.3 Wind Systems

Mechanical wind pumps typically consist of a windmill (i.e., rotor) and transmission (gearbox or other types) mounted on a tower. Most often, rods connected to the transmission drive a down-hole piston pump. Wind pumps are typically characterized by:

- high capital equipment costs and relatively low recurrent costs for operation (because there is no fuel requirement), maintenance, and repair;
- limited capacity given the rotor diameter on commercially available machines (up to 7.6 meters) and wind regimes that are commonly encountered (less than 5 m/s under fairly favorable conditions);
- no on-demand pumping capability, which necessitates providing a large amount of storage capacity to increase water availability;
- the possibility of local manufacture;
- no portability; and
- mechanical controls, which permit unattended operation.

[2] Although it is very unusual, it is possible to install several stacked PV submersibles in one well to increase output from a single source. However, this is usually not economically viable.

4.4.4 Hand-Operated Systems

Hand-operated pumps are commonly simple lever arms that move piston, diaphragm, or rotary down-hole pumps. They are characterized by

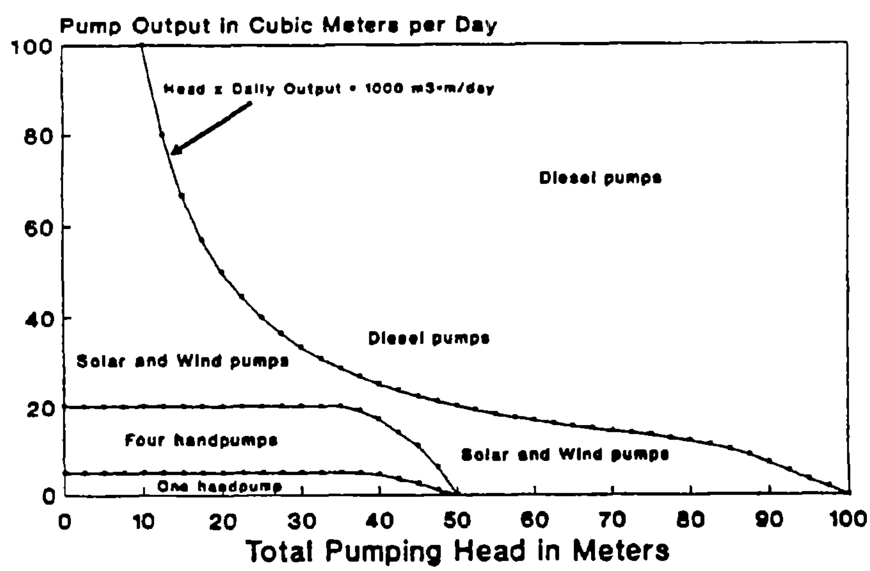
- very low capital and recurrent costs;
- ease of installation, operation, and maintenance;
- very limited capacity for single units—less than about 6 m^3/day for up to 40-50 meter heads, but more at lower heads; and
- the possibility of local manufacture for some simpler models.

4.5 Other Types of Drivers

This manual does not deal specifically with other system types besides the four described above. The approximate head and flow limits for the pump drivers discussed here are given in Figure 11. Six other kinds of pump drivers and one other configuration (hybrid systems) might be of potential use to some readers. Thus, the following are briefly described here (see Fraenkel 1986 for coverage of an exceptionally wide variety of pumps):

- electric generators and grid-connected pump sets;
- wind-electric turbines;

Figure 11.
Approximate Output and Head for
Diesel, Solar, Wind, and Hand Pumps



Notes: 1. Solar and wind pump output depend on radiation and wind speed level.
2. At low head and low flow, all equipment options are possible.
3. Lines indicate technical limits of capacity for existing equipment under normal use conditions.
4. Based on 3.5 m/sec wind speed, and 6 kWh/m^2/day solar radiation.

- animal-traction pumps;
- biogas or dual-fuel pumps;
- river current turbines;
- hydraulic rams; and
- hybrid systems.

4.5.1 Electrically-Driven Pump Sets

Where electric power is available, grid-connected pump sets are usually the most cost-effective system option for rural water supply. Compared to diesel-driven pumps, electric sets are generally easier to install, require less maintenance, and use cheaper fuel (electricity as opposed to diesel or gasoline). However, for sites without any grid electric power, the high cost of extending an existing grid to more remote areas usually makes other pumping alternatives more cost-effective. One major problem in some countries is a notoriously unreliable electric power system. Countries such as Sudan and Somalia often experience rotating brown-outs or black-outs which can last up to more than a week in some areas. This situation clearly requires some backup means of obtaining water.

In some countries, diesel-driven generators are used to power electric pumps. For sites with other noncompetitive end-uses for the electricity (e.g., village lighting or grinding grain at night), diesel-powered electric generators for water pumping may be cost-effective. In general, such systems offer the flexibility of using electric pump motors, but are inefficient from an energy perspective in that the energy is converted from chemical to mechanical to electrical form and then back to mechanical. Extensive cost data that would permit comparisons with alternatives are unavailable. These systems also require components that are more complex and difficult to repair locally (e.g., electric generators). They also demand additional skill to maintain and repair and, hence, entail associated training needs. This is a fairly uncommon application in many developing countries, so it will not be discussed further in this manual.

Finally, local "mini-grids" have been suggested as a way of powering electric pumps in rural areas distant from a national grid. Mini-grids—relatively small units in terms of power generation (about 500 kW)—could power a variety of loads in a local area, such as motors and lighting for cottage industry, village lighting and communications, and pumping for the rural water supply. Again, this approach has some merit, but it is fairly rare at present and will not be considered here.

4.5.2 Wind-Electric Turbines

Wind-electric turbines received a considerable boost in popularity in the United States and Europe during the late 1970s and early 1980s when over 15,000 were installed in California. These machines were sited in areas with average wind speeds of more than 7 m/sec, a speed that is rare on a regular basis in most areas near where people live. Wind-electric turbines are usually designed to operate most efficiently at higher wind speeds than are mechanical wind pumps.

Where high wind speeds prevail (i.e., greater than 6 to 7 m/sec), wind-electric turbines can be the most cost-effective choice for power generation at remote sites. However, such high average wind speeds are not usually found in developing countries. Direct water-pumping applications for wind-electric turbines are still in the development stage, and there is little long-term data on recurrent

O&M costs. For these reasons, they will not be discussed further here. However, where windspeeds are sufficient, the potential of this new and interesting application of wind power deserves to be monitored as developments occur.

4.5.3 Animal-Traction Pumps

Animal-drawn pumps (ADPs) have been used to supply water for drinking and small-scale irrigation for thousands of years in countries such as Egypt and Iran. Recent research on ADPs[3] has focused on increasing their efficiency and reliability, lowering their capital costs, and developing units that can be manufactured in developing countries. Work has been undertaken in countries like Botswana[4] to develop an animal-drawn transmission that can be used in conjunction with a standard pump, such as the Mono. While many low-flow, relatively low-efficiency animal-traction pumps are being used around the world, very little cost data is available on improved versions that might be relevant to the applications covered in this manual.

4.5.4 Biogas and Dual-Fuel Pumps

Biogas pumps are slightly modified internal combustion engines (usually diesels) which burn biogas, a product of the decomposition of a biomass. The main combustible component of biogas is methane, but it also contains other gases such as carbon monoxide. Biogas pumps have been used experimentally in many countries (e.g., India and Botswana) but have not yet achieved widespread commercial acceptance. Dual-fuel engines are also used to drive water pumps. The two fuels are usually diesel fuel (to get the engine started) and biogas or producer gas from a biomass gasifier (to run the engine after it gets warmed up). Gasifier pumps have been used in the Philippines and Thailand for irrigation pumping but, again, have achieved no significant share of the pumping market (nor, it must be said, have wind or solar pumps). The primary advantage of these engines is that they use renewable energy resources and, depending on the country where they are used, show some potential for taking the place of imported fossil fuels. Their primary disadvantage is that they have all the attendant O&M limitations of diesel pump operation, requiring frequent and often extensive maintenance and repair, due to the typical impurity of their fuel.

4.5.5 River Current Turbines

River current turbines are basically modified paddle wheels which are installed in rivers or streams. The water current drives the pump blades in a circular motion, which is usually mechanically converted into a reciprocating motion to drive a piston pump. The pumps are typically used in low-head, low-flow applications. These pumps have been used experimentally in (among other countries) Mali and Southern Sudan but thus far have achieved no significant commercial success. While they have the distinct advantage of being locally manufacturable in many countries, they have not gained a reputation for being robust enough to attract many potential customers. Research on river current pumps is continuing in several developing countries.

[3] Kennedy and Rogers 1985.

[4] See Hodgkin, McGowan, and White 1988, Vol. V.

4.5.6 Hydraulic Rams

In certain situations, hydraulic ram pumps are an extremely useful technology for pumping water. Relatively simple in design and construction, locally manufacturable in many countries (e.g., Nepal and Indonesia), and very durable, they can effectively lift water up to 150 meters, using no external power supply other than the energy in falling water. They use the potential energy of water falling a certain distance to lift a smaller amount of water up a greater distance. The major constraint is that their application is strictly limited to sites that have the necessary altitude difference between the water source and the pump to drive the ram. This situation occurs often enough in some countries, particularly in South and Central America and some parts of Asia, that rams are an important pumping technology, if somewhat limited in widespread applicability.

4.5.7 Hybrid Systems

One disadvantage of nearly every type of pumping device is that it occasionally runs out of the energy resource used to drive it——diesel fuel is sometimes unavailable, the wind stops, or there are several cloudy days in a row. To address this problem, hybrid systems that use more than one power supply (e.g., diesel/wind, wind/PV, or diesel/handpumping systems) have been employed where the demand for water is critical and outages cannot be tolerated. Hybrid systems are always more expensive than traditional systems with a single driver.

An example of a hybrid system is PV/diesel, where PV powers an electric submersible pump whenever solar radiation is sufficient. If the array, which is the main driver, produces insufficient power because of several cloudy days in a row, the diesel engine is automatically engaged by the electronic controller and pumps water until the PV unit can again produce sufficient power. Such systems normally use a single pump with two drivers. Since the diesel unit consumes fuel only when it is running, there is no penalty (aside from the engine's initial capital cost) for having it always available in reserve.

While backup systems are similar to hybrids, they usually use completely redundant systems. An example is a village water supply system that has several different water sources. A small diesel engine is installed to pump from the best source as the primary pumping unit. When water becomes unavailable for whatever reason (e.g., breakdown of the diesel engine, need to perform maintenance, or depletion of the water source), handpumps installed at another site(s) are used as backups. However, in most situations, handpumps cannot supply the same amount of water as the diesel engine, so a reduced supply must suffice until the primary diesel system is again operational.

An alternative to purchasing and installing hybrid or backup pumps is using larger storage tanks. If sufficient water can be pumped during normal operation so that enough water for several days is available in a storage tank, users will have an adequate supply in the event of system failure.

The next four chapters discuss detailed procedures for designing diesel, solar, wind, and handpumping systems. All are based on the fundamental pump characteristics discussed in this chapter.

Chapter 5: Diesel Pumps

As the most common type of prime mover in much of the developing world, diesel engines are used to drive a wide variety of pumps. In many countries, there is a broad national network (formal or informal) of equipment distributors, local dealers, mechanics, and transportation facilities that supports diesel engines used for pumping and other purposes. In most cases, diesel pump sets are the standard against which all other types of pumping systems must be compared. Besides the technical questions of power output and speed, the two major factors to consider in choosing an appropriate diesel engine are its manufacturer and model. Look for a manufacturer with a good reputation for quality products. It is important to consider the local availability of equipment, experienced technicians, engine configurations, and dealer support of spare parts inventories. The choice of model depends on the site conditions.

5.1 Engine Description

Diesel engines can be used to drive almost any type of pump through drive shafts or pulleys and belts. They can also drive electric generators to run electric pump sets, which is advantageous when submersible pumps are appropriate but grid electricity is unavailable. However, this manual addresses only the direct mechanical application of diesel engines to water pumping, which are much more common.

The range of diesel engine output is essentially unlimited, with units available from 2 kW to 200 kW or more. This manual focuses primarily on the 2 to 50 kW range for small-scale water pumping. For larger systems (for large scale irrigation, for example) a more complex design procedure is required than that given here. Diesel pump sets are usually characterized by moderate capital costs and comparatively high recurrent costs for fuel, maintenance, and repair. They are relatively portable, since engines up to 10 kW normally weigh less than 200 kg. Two typical small engines (under 10 kW) and one larger engine (40 kW) are shown in Photographs 2-4.

Diesel engines are internal-combustion engines that use diesel fuel (also called gasoil) as an energy source. They normally have compression-ignition systems, meaning that the fuel is ignited by the high temperatures in the combustion chamber produced during the engine's compression stroke. Spark plugs are not normally used in diesel engines, except in rare instances that will not be considered here. Diesel engines are generally categorized in the following ways:

- high- or low-speed—operating at greater or less than about 2,000 revolutions per minute (rpm);
- single- or multi-cylinder—bigger, more powerful engines have a greater number of larger cylinders;
- air- or water-cooled; and
- two- or four-stroke.

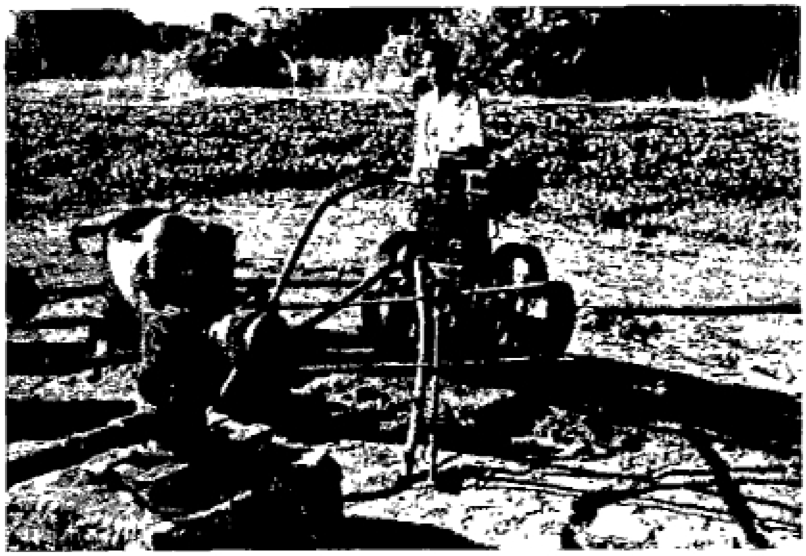


Photo 2.
Lister diesel engine with shaft turbine pump for irrigation in Sudan.

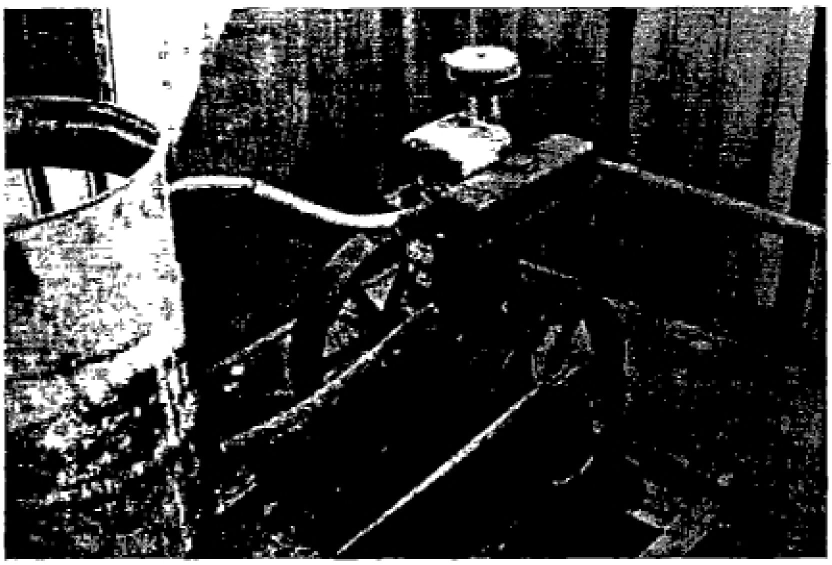


Photo 3.
Lister diesel engine with Mono pump for village water supply in Botswana.

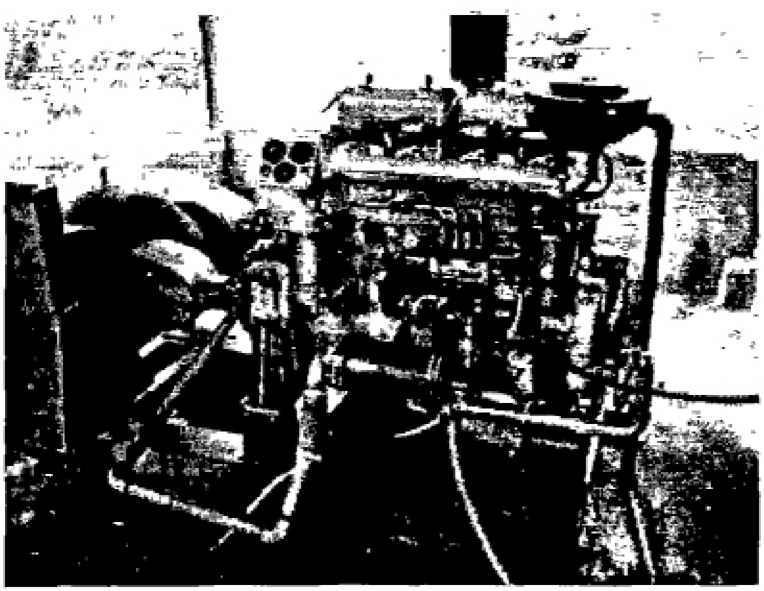


Photo 4.
Italian Lambardini diesel engine with centrifugal pump for irrigation in Somalia.

Traditionally, diesel engines for water pumping have been slow-speed, relatively long-lasting engines. Those that are clearly built for long service are generally heavy; they often run at lower speeds (less than 2,000 rpm) and tend to be more expensive in terms of the initial cost. However, they are often more durable and easier to work on when maintenance or repairs are required because of their simple design. The higher speed, lighter engines that are now becoming available tend to be less expensive initially but also to have a shorter service life. Some lighter, high-speed Japanese diesels fall into this category. From the standpoint of life-cycle costs (see Chapter 10), it is not always obvious which is the best choice. Deciding between low- and high-speed engines will depend on other factors, such as funds available for the equipment purchase, availability of spare parts, and quality of service.

Single-cylinder engines typically have rated power outputs between 2 and 10 kW. Multi-cylinder engines are available in a variety of sizes starting at about 8 kW. They tend to run more smoothly than single-cylinder engines but are normally more expensive. Whether you use a single or multi-cylinder engine depends primarily on power requirements.

Water-cooled engines tend to be larger and somewhat quieter-running; they often do not require a cooling fan and/or fins as air-cooled units do, but involve the (additional) maintenance of coolant level in the radiator. Large air-cooled engines need a cooling fan (small ones sometimes rely only on fins), which causes a small power loss. Most engines under 10 kW are air-cooled.

Both two- and four-stroke diesel engines are available. Two-stroke engines have fewer moving parts, tend to operate at higher speeds and wear out faster, are less efficient, and have a higher power-to-weight ratio (i.e., they produce more power per kilogram of engine weight). Oil must be added to diesel fuel for the proper operation of two-stroke engines. Otherwise, damage to the engine may result. For most water pumping applications, four-stroke engines are preferred.

Diesel engines also differ in the ways that they transmit power to the pump. Some are connected to the pump shaft through a gear box, and others through belts and pulleys. Transmissions involve power losses that have to be accounted for in engine sizing (see Section 5.3 below).

5.2 Selecting a Manufacturer

Diesel pumping systems are widely used in most developing countries, so many types of engines are usually available. The most important question to ask when choosing a manufacturer is whether you have ready access to adequate spare parts and trained local mechanics who can repair the engine. Give careful consideration to the make of the equipment, the product support provided by the manufacturer and its local representatives, and operating and repair capabilities in that particular area.

Be careful if you are considering "offshore"[1] purchases of mechanical equipment through other than local suppliers, or when buying any equipment that is not already supported locally. Even if some spare parts are included with the original offshore purchase, more will eventually be needed. In addition, any specialized repair tools that may be required and are not available locally will have to be

[1] Offshore here means equipment that is not already available through established local distributors. It does not refer merely to any imported equipment.

purchased directly from the manufacturer, and local mechanics will probably not be familiar with the equipment and its idiosyncrasies. For all kinds of systems, long-term, trouble-free operation depends largely on local capabilities to service and repair the equipment when necessary. The quality of equipment and the service infrastructure vary considerably among countries as well as within a country or region.

It is wise to carry out an informal survey of locally available equipment before deciding what to purchase. Discussions with dealers and local engine overhaul shops can help determine spare parts availability and can identify particular makes and models with good reputations as well as those prone to problems. At this stage, you can learn about specific installation and operational features that may affect your choice. Consult several sources to confirm information and opinions, since individuals usually have their own preferences, justified or otherwise. While the initial cost plays an obvious role in selecting a particular manufacturer's equipment, lower initial cost may mean lower quality equipment that will be expensive to maintain later on.

5.3 Choosing an Engine Model

After selecting the appropriate flow rate and determining the total head, the power requirement can be calculated as described in Chapters 2 and 3. A particular model of diesel engine is then chosen on the basis of this power requirement. The performance of any diesel engine is usually specified by manufacturers in terms of:

- torque;
- power; and
- fuel consumption.

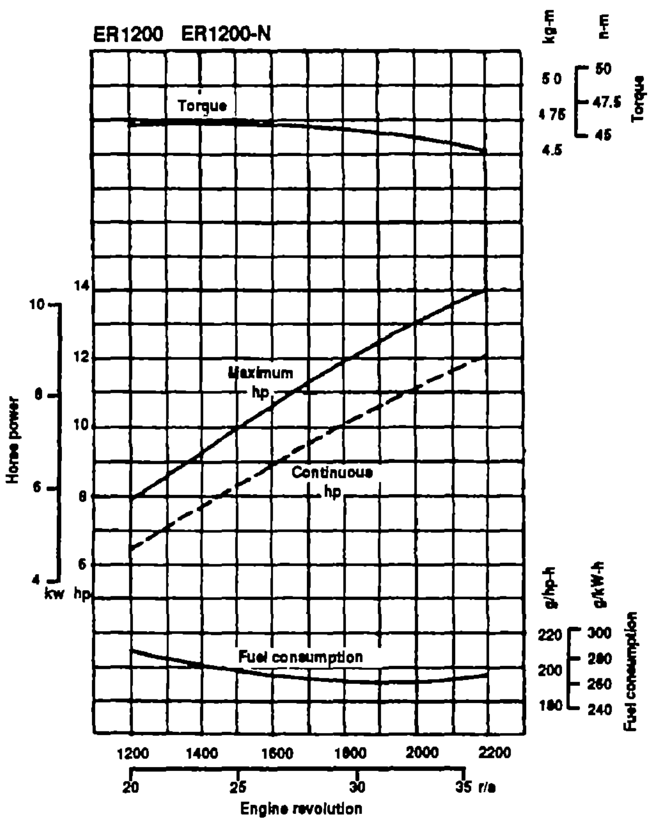
All vary with engine speed, so they are quoted for specific speeds or given for a range of speeds in graph form. Examples of typical diesel-engine performance curves for torque, power, and fuel consumption are shown in Figure 12. Fuel consumption (grams of fuel consumed per hour of operation) increases with engine speed. **Specific** fuel consumption (in grams of fuel consumed per kilowatt hour output) can increase or decrease with engine speed. In Figure 12, the Kubota ER 1200 is designed to operate most efficiently (i.e., at the lowest point on the fuel consumption curve) around 1900 rpm, while the Lister STI operates most efficiently at 1500 rpm.

In the Kubota diagram, there are two power output curves. The upper one is for maximum rated power output and the lower for continuous output. Systems should be sized so engines run continuously at or below the continuous output curve. This means the continuous power rating of the engine selected should be greater than or equal to the power requirement of the pump.

Engine performance is always given for specific conditions of temperature, air pressure, and relative humidity, since these variables also affect performance. Fuel consumption is quoted for a given power output at full engine loading. Engine loading is the ratio of power required by the pump to the maximum de-rated (see definition below) power available from the engine (see Example 7). As discussed in the following sections, both the condition of the engine and its loading affect fuel consumption and maintenance requirements.

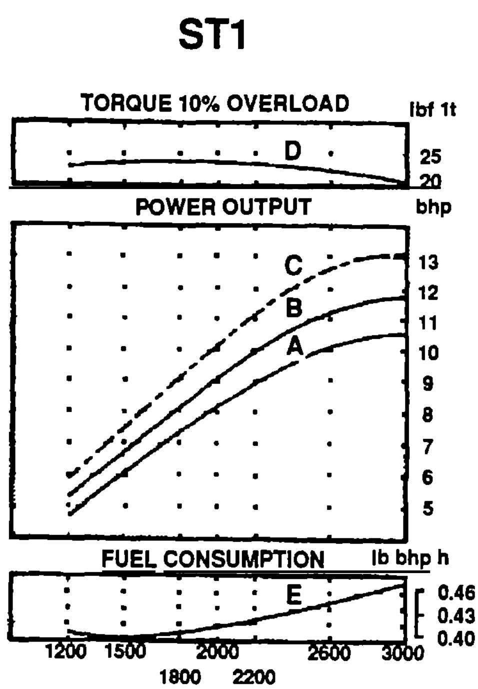
Figure 12 (a,b,c)

Figure 12a. Kubota ER1200



*This performance curve is rated on the basis of JIS (Japan Industrial Standard).

Figure 12b. Lister ST1



A = Continuous Power Output
B = Intermittent Power Output
C = Maximum Gross Power

Figure 12c.
Power Output and Fuel Consumption for a Lister ST-1 Diesel

Engine Speed	Continuous Power kW (Hp)	Maximum Power kW (Hp)	FC (g/kWh)
3000	7.8 (10.5)	8.7 (11.7)	280
2600	7.5 (10.0)	8.4 (11.2)	267
2000	6.0 (8.1)	6.7 (9.0)	250
1800	5.4 (7.3)	6.0 (8.1)	245
1500	4.5 (6.0)	5.0 (6.7)	240
1200	3.5 (4.7)	3.9 (5.2)	245

The "nameplate" power rating of a diesel engine, which is stamped on the manufacturer's nameplate, is the power available under continuous full-load conditions (i.e., when the load or pump is drawing the full rated power from the engine) at the engine speed indicated and under specified conditions of temperature, air pressure, and humidity. The power available from an operating engine will normally be less than the manufacturer states because operating conditions are unlikely to match those of the nameplate rating. Diesel engine output is "de-rated" or reduced by a certain percentage to account for such differences in conditions. An engine's power output can be calculated using manufacturer's specifications and then de-rating the engine for the specific site and operating conditions. De-rating recommendations vary by manufacturer and engine, but Lister gives these typical de-rating factors for the following conditions:

- for high engine-air inlet temperature, de-rate the power output by 2 percent for every 5.5^{o} above 30^{o} Centigrade;
- for lower barometric pressure (i.e., higher site elevation), de-rate by 3.5 percent for every 300 meters of elevation beyond 150 meters above sea level;
- for high humidity, which is also dependent on temperature, de-rate up to 6 percent (the precise value has to be chosen from a table supplied by the manufacturer);
- for power-absorbing equipment, common de-rating factors are up to 10 percent for motor-driven radiator fans, 5 percent for belt drives, and 3 to 5 percent for transmissions; and
- poorly maintained engines (e.g., heavily carbonized) may also require a further de-rating of 5-10 percent.

These de-rating factors are calculated individually and then added. The total de-rating percentage is subtracted from 100 percent and then multiplied by the rated power for a full load to determine the de-rated output for the rpm specified, as shown in Example 6.

Example 6: De-Rated Power Output

A well-maintained Lister ST-1 has a nameplate rating for continuous output of 6 kW at 2,000 rpm (see Figures 12b and 12c). It will be operated at 1,500 rpm at a site 750 meters above sea level where the temperature can be expected to reach 38^{o} Centigrade in the summer and where the humidity is negligible. A pulley-and-belt system will be used to drive the pump. What is the actual power output that can be expected under these conditions?

At 1,500 rpm, the Lister ST-1 develops 4.5 kW under standard conditions, according to the manufacturer's data. The de-rating factor for altitude is:

$$((750\text{m} - 150\text{m})/300) \times 3.5 \text{ percent} = 7 \text{ percent}$$

The de-rating factor for temperature is:

$$((38°\text{C} - 30°\text{C})/5.5°\text{C}) \times 2 \text{ percent} = 3 \text{ percent}$$

Belt losses call for de-rating by 5 percent. Adding these factors together, the total de-rating factor is 15 percent. Thus, the maximum de-rated power that can be delivered by an ST-1 operating under these conditions will be:

$$4.5 \text{ kW} \times (1 - 0.15) = 3.83 \text{ kW}$$

Each manufacturer's literature should include information on standard conditions and de-rating calculations. The total de-rating factor can easily be 20 to 25 percent. In practice, this means the power that can be expected from an engine may be only 75 to 80 percent of the rated power indicated in the specifications for a chosen speed. Selecting an engine based on nameplate output alone can mean purchasing a unit that will not be able to meet the pump power requirements.

Once the de-rated output for an engine has been calculated and matched to the pump's power requirement, an engine model can be chosen. In doing so, engine loading should also be taken into account. Remember that loading is a measure of the *power required* of an engine relative to the maximum de-rated *power it is capable of delivering*. Loading does not depend on the total volume of water pumped, but rather on flow rates and head—it is dependent on power, not energy.

Under most conditions, an engine should be overpowered by 20 to 30 percent (i.e., run at a loading of 70 to 80 percent). Normally, diesel engines are most fuel-efficient at these levels, and a margin of power is available to meet unusually heavy operating conditions, such as at start-up. Engines operated at low (30 percent or less) loading run cooler, decreasing fuel efficiency and increasing carbon buildup in the cylinder(s) and exhaust manifold, which increases maintenance requirements and costs.

Example 7: Engine Loading

The diesel engine in Example 6 is coupled with a pump that is 60 percent efficient and delivers 36 m^3/day from 75 meters of head, running at a constant rpm over a 6-hour period. What is the engine loading?

First, determine the power requirement for the load. From Formula #5 for hydraulic energy (E_h) demand given in Section 3.1:

$$E_h = .00273 \times 36 \text{ m}^3\text{/day} \times 75 \text{ m}$$

$$E_h = 7.4 \text{ kWh/day}$$

Since power equals energy divided by time, the actual power (P) input to the pump is then:

$$P = 7.4 \text{ kWh/6 hours/60 percent} = 2.0 \text{ kW}$$

Since the de-rated power output of this engine (from Example 6) is 3.83 kW, the loading will be as follows:

$$\text{loading} = 2 \text{ kW/3.83 kW} = 52 \text{ percent}$$

This is somewhat lower than desirable (70-80%). Operating the engine at a slightly lower speed (say, 1200 rpm) would improve the loading, because the de-rated output would then be:

$$3.5 \text{ kW} \times (1 - 0.15) = 2.98 \text{ kW}$$

(still more than the required 2.0 kW)

and the loading would then be:

$$2/2.98 = 67\%.$$

Under-loaded engines—running at less than 50 percent of full-load conditions—are common in developing countries. The reasons include improper determination of head as well as poor engine and/or pump sizing and matching. Also, for the very low power demands encountered with some small-scale applications, it may not be possible to select an engine which is small enough and has a slow enough speed to permit proper loading (70 to 80 percent) due to the limited availability of small diesel engines and/or limited yield of the water source. The lower limit of diesel engines that are commonly available is about 2 kW. There are some engines as small as 1 kW, but they are uncommon. In such cases, alternatives to diesel engines should be considered.

The fuel and lubricant consumption of a diesel engine accounts for a significant portion of its operating costs. Lubricant use (including oil changes) should be in the range of 3 to 5 percent of fuel consumption by volume. As shown in Figure 12, fuel consumption is dependent on the engine's full rated power (as specified by the manufacturer) and loading conditions. Full-load fuel consumption (FLFC) is often given by manufacturers in grams of fuel consumed per rated kWh (g/kWh) or some similar measure such as pounds of fuel consumed per brake horsepower-hour, as in the Lister curve in Figure 12. For small-scale applications, you would normally be interested in the fuel consumption of a specific engine in terms of liters per operating hour (l/hr). To convert to these units, the calculation is:

$$FLFC = {}^{g}/_{kWh} \times ({}^{.001}/_{SG}) \times kW$$ ***Formula #7***

where FLFC = full-load fuel consumption in l/hr

g/kWh = fuel consumption[2] in grams per kWh

SG = specific gravity of diesel fuel (usually 0.87)

kW = engine's rated full-load power output for a specific rpm (*not de-rated*)

As an approximation, actual fuel consumption can be estimated as the engine's FLFC in l/hr multiplied by the loading, which will be reasonably accurate down to a (very low) loading of 20 percent[3]. Below 20 percent, fuel consumption does not decrease much. Note that engine de-rating does not affect this calculation.

[2] If your engine's specific fuel consumption is given in terms of pounds per brake horsepower per hour (lb/bHp/h), multiply by 609 to get g/kWh. For example, 0.4 lb/bHp/h x 609 = 243 g/kWh.

[3] Note that this is an approximate calculation, because the engine's fuel consumption is not a strictly linear function of FLFC. However, in practice, other factors such as engine conditions and fuel spillage make this a good practical estimate.

Example 8: Fuel Consumption

Calculate the expected fuel consumption for the Lister ST-1 engine from Example 7.

From Fig. 11b, the full load fuel consumption (FLFC) for a Lister ST-1 operating at 1500 rpm is about 0.39 lb/Hp-h. Using the conversion factor given in footnote 2, this equals 237 g/kWh. Then, from Formula 7, the FLFC in liters per hour is:

FLCF = 237 g/kWh x (.001/.87) x 4.5 kW = 1.23 l/h

At the loading of 52% calculated in Example 7, actual fuel consumption would then be 1.23 x 52% = 0.64 l/h. This figure will depend to some extent on the condition of the engine (it will be somewhat higher if the engine is in poor condition), but it is a good estimate.

For given engine, pump, and site conditions, fuel consumption per cubic meter of water pumped will depend on the loading. *At a lower loading, the engine will consume more fuel per unit of water pumped.* Using the same procedure given in Example 8, you could calculate the difference that loading makes in fuel consumption per unit of water pumped (using a more precise but complex relationship between fuel consumption and loading than that given above). For example, if you have a Lister ST-1 that is used to pump 30 m^3/day from 90 meters of head, you can vary the flow rate and, hence, the loading by changing the engine speed. Assuming that the head remains essentially constant, annual fuel consumption for the two different loadings would be 1,830 liters at a loading of 34 percent and 1,430 at 73 percent. This represents a savings in fuel and lubricant costs alone (per unit of water pumped) of over 22 percent, not to mention the reduction in maintenance costs associated with running the engine warmer and thereby reducing carbon buildup[4]. An alternative approach is to use a smaller engine at a higher loading. In that case, you would also save money on capital equipment costs, in addition to lower operating, maintenance, and (eventually) engine replacement costs. This shows the importance of proper loading in the design of diesel pumping systems.

5.4 Cost Considerations

Cost considerations include initial equipment and installation costs as well as recurrent costs for operation and maintenance. The initial installed cost of a diesel pumpset includes more than just the capital cost of the engine and pump. It also includes labor for the installation, transportation, and the cost of other equipment and materials including cement, fencing, a pump house, water meters, non-return and gate valves, and piping, among other items. Diesel engine costs vary considerably depending on the size and procurement source. In 1990 typical cost ranges were as follows:

- US$300 to US$600 per kW for units between 2 and 10 kW, with smaller engines being more expensive per kW; and
- US$200 to US$500 per kW for units between 10 and 25 kW, with smaller engines again being more expensive per kW.

[4] Note that this is an extreme example to demonstrate that loading can significantly improve fuel consumption.

These figures do not include ancillary equipment, such as transmissions, gearboxes, and fuel storage tanks. There are several reasons these cost ranges are so broad. The cost of a diesel engine reflects both its quality and source of origin. For example, Lister (now Lister-Petter) engines are the workhorses of much of Africa. Manufactured largely in the United Kingdom, they are generally recognized to be very reliable, long lasting, and robust. Compared to many alternatives, they are also expensive. As a result, many (especially private) users have turned to much cheaper (and in many cases, much lower quality) diesel engines made in countries such as India or China. For example, in Sudan a new Lister 8 kW single cylinder engine costs about $2,200. A comparably sized engine manufactured in India costs only about $600. While the Lister may have higher actual power output and last four times as long as its competitor, people are increasingly unwilling to pay the price differential for higher quality. The inevitable trade-off is that lower quality engines often have lower actual power output, need more maintenance, break down more often, and have much shorter lifetimes. A lack of adequate access to credit financing often prevents people from considering using the higher quality machines (see Chapter 10 on Life Cycle Cost).

Recurrent operating costs include labor for a pump operator (if that individual is paid), fuel, lubricants, and consumables. The cost for a pumper typically falls at the lower end of rates for local skilled labor. In some cases, a pumper's duties can be combined with other related activities (e.g., serving as a caretaker or guard), thereby reducing the cost of employing a pumper. Depending on local labor rates, pumper costs can be one of the most important recurrent system costs (see Chapter 10). Fuel and spare parts costs can be very high in areas where fuel and parts are scarce, and can amount to as much as 50 percent of system capital cost (for cheaper systems) *per year*.

5.5 Maintenance and Repair

Maintenance requirements can be categorized as preventive or corrective. **Preventive** maintenance includes servicing that should be done on a routine basis to ensure efficient operation of the system. **Corrective** maintenance is required for occasional problems that may lead to engine or pump failure, but are not part of normal servicing. Corrective maintenance can also be in response to a breakdown. Corrective maintenance is typically unscheduled service.

Preventive maintenance is service that is carried out on a routine basis, according to the number of hours of engine use or a regular schedule. In practice, servicing is often not performed regularly, so corrective maintenance is required after the engine has broken down. This has obvious consequences for the reliability of the system and the lifetime of the equipment. Breakdowns occur for a wide variety of reasons, including poor installation, a lack of operator attention, failure to provide regular service, or poor-quality servicing. The underlying causes of frequent breakdown may be complex and may include a poor understanding of the system, lack of incentives for pumpers to perform well, or funding problems. For "circuit rider" maintenance and repair teams, all necessary corrective maintenance should be undertaken during regular service visits to sites to minimize unanticipated breakdowns.

A diesel engine requires an operator (or pumper), regular servicing, and periodic repair. The pumper's skill and the quality and amount of servicing and repairs that are required are completely interdependent. An operator is responsible for day-to-day operation of the pumping system, including starting and stopping the engine and replenishing the fuel. The pumper is also responsible for preventive maintenance, such as checking the oil (and changing it when required), tightening loose nuts and bolts, and other minor tasks. Corrective maintenance is usually performed by a mechanic, whose tasks include decarbonizing the engine, cleaning injector nozzles, replacing worn belts, adjusting valve clearances, and changing the oil, air, and fuel filters. Checking the fuel-injection system and cooling system and replacing other worn components as necessary are also part of periodic service requirements.

The manufacturer's literature provided with the engine should indicate proper intervals for servicing (see Appendix C for an example of a diesel engine maintenance schedule). To give a sense of the range of normal service requirements, oil changes are typically required after every 250 hours of engine operation and decarbonization after every 1,500 hours. The actual requirements for a particular system may vary with the operating environment, application, and mechanic's skill and training. For example, if the engine is operating at a low loading, the decarbonization interval should be shorter. Very often, because engines do not receive proper maintenance, the risk of breakdowns is increased, the overhaul interval is shortened (which increases costs), and the lifetime of the engine is shortened. Almost without exception, the routine maintenance for diesel engines is the weakest aspect of the service infrastructure.

Corrective maintenance, which is required when unanticipated problems occur, includes such activities as replacing worn belts or fuel-tank straps, as well as decarbonization or engine overhauls, if these are not performed as part of scheduled preventive maintenance. Proper corrective servicing will eliminate the need for much curative maintenance.

The rate of breakdowns and unscheduled service is heavily dependent on the operator's attentiveness and the normal servicing which the engine receives. Routine preventive maintenance, such as changing the engine oil and replacing filters, is one of the most important factors in minimizing repair costs. However, at least one breakdown per year (and possibly more) that requires corrective maintenance is fairly typical, depending on the engine's age and condition and the quality of service it has received.

The cost of unscheduled servicing is highly variable. Estimates of service and maintenance costs, not including fuel and labor, are in the range of US$0.15 to US$0.25 per cubic meter of water delivered and may vary further depending on labor costs, operator skill, and equipment quality. This means that typical annual O&M costs, excluding expenses for fuel and operator labor, range between 25 and 75 percent of the engine's initial cost.

5.6 Equipment Life

The service life of any device depends on the conditions under which it is used, which includes installation and maintenance. Under optimum conditions, an engine should be replaced when the cost of maintaining it exceeds the amortized cost (see Chapter 10) of purchasing a new one. However, users' perceptions of engine life also play a role. If users anticipate getting five years of service, a new engine may be purchased at five years even though the old one is still functional. Light, high-speed engines are likely to have shorter lifetimes than heavy, slow-speed models. The best way to estimate values for equipment lifetimes in your situation is to ask other engine users, local equipment dealers, and operators of repair shops about their experiences with the makes and models you are considering.

Usually, the lifetime of an engine is given informally in years. The normal range is from 3 to 4 years (for lower quality, heavily used, and/or poorly maintained engines) to 20 years or more (for higher quality systems that are reasonably well maintained and overhauled at regular intervals). Lifetime hours of operation vary from under 5,000 to over 50,000 hours. About 20,000 hours is a reasonable approximation for planning and costing purposes.

Chapter 6: Solar Photovoltaic Pumps

Solar photovoltaic (PV) cells are used to convert sunlight directly into electricity. While PV power can be used for a variety of end-use applications (e.g., telecommunications, lighting, and refrigeration at health clinics), it is becoming increasingly popular for water pumping in remote areas. As of mid-1992, it is estimated that between 10,000 and 15,000 solar pumps have been installed around the world. Successes in PV research and development have significantly reduced costs and increased the reliability of this power source, which has historically been very expensive. Multiple PV cells (30 to 50) are mounted on a single unit (about 0.3 by 1.2 meters) called a module. The individual modules are wired together in groups (just like batteries) to form arrays. While the PV arrays themselves are exceptionally reliable and long-lasting power sources, the primary limitation on the use of solar pumps has been and continues to be the high initial capital cost of a system. Also, since water output is directly proportional to the level of solar radiation falling on the modules, relatively high and uniform solar radiation must occur at your site for solar pumps to be a cost-effective choice.

Solar pumps have been used in field applications for about 14 years (as of 1992). Some early (mid-1980s) models were plagued by design and manufacturing problems. Considerable gains in increasing system efficiency and reliability and reducing production costs have lowered the cost per unit of water delivered. Still, solar pumps remain fairly expensive compared to other pumps, although they are cost-effective pumping options under certain circumstances. This section describes typical system components as well as the design, operation, maintenance, and repair requirements of solar pumps.

6.1 System Description

As PV pumps continue to become more popular, an increasing variety of designs is becoming available that differ in cost, application, capacity, and reliability. This section describes the most common kinds of solar pumping systems and several types of optional components. The focus is on systems that have been field-tested in evaluation programs in countries such as Botswana[1], Mali, Malaysia, and Sudan[2].

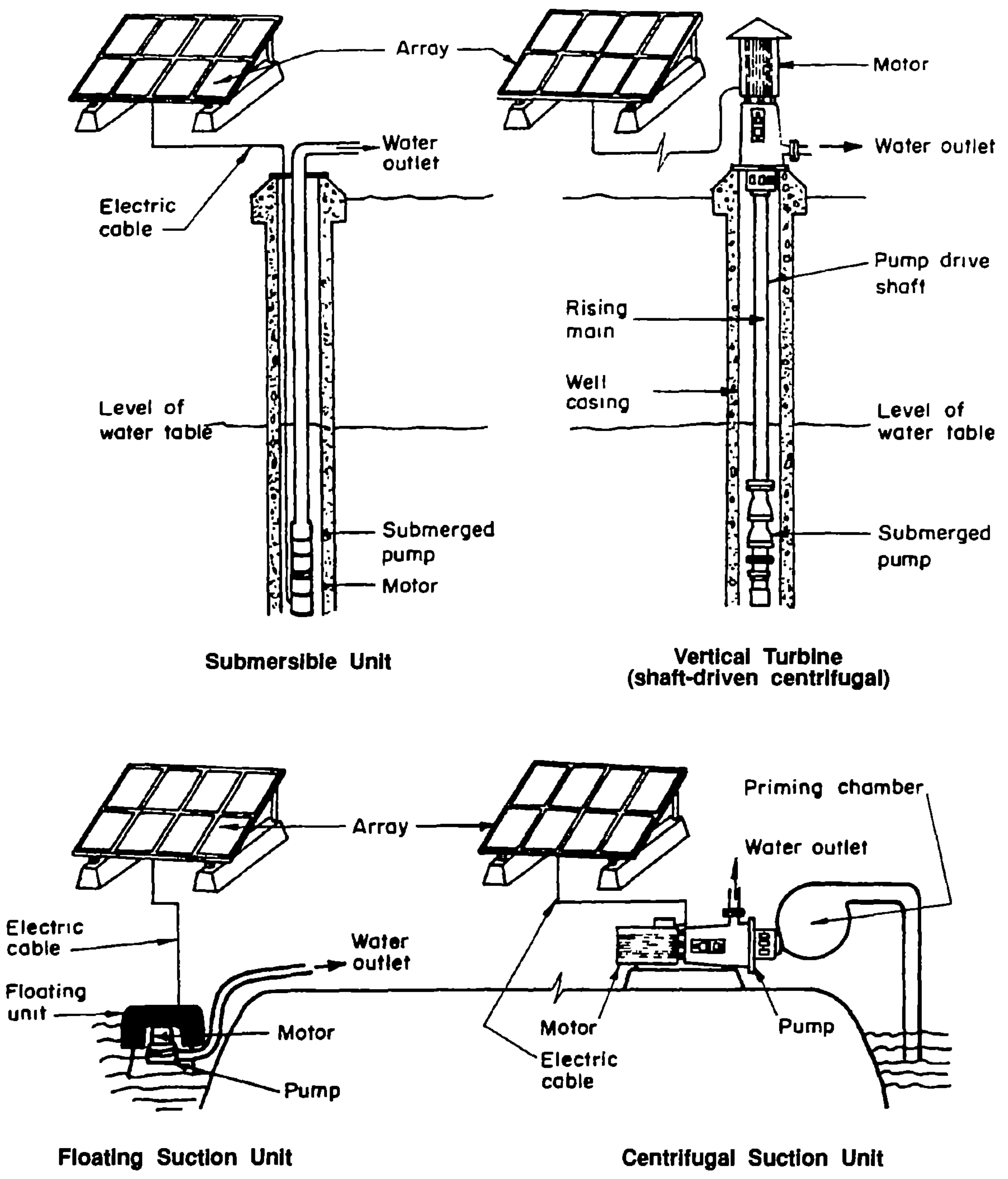
The most basic PV pumping system consists of an electrical power source (the array), a motor, and a pump. Electricity from the array goes to the motor, which drives the pump. Many variations of this simplest type of system use different optional components. More complex designs are intended primarily to increase the efficiency or reliability of the water supply, so more water can be pumped with a PV array of the same size. Schematic drawings of several typical solar pumping systems (sub-

[1] Field tested under the USAID-Botswana Renewable Energy Technology Project, implemented by ARD 1983-87. See *Small-Scale Water Pumping Systems in Botswana, Vol. 4--Solar Pumps*, R. McGowan and J. Hodgkin, ARD, 1988.

[2] Field tested under the Sudan Renewable Energy Project (Phase II), implemented by ARD 1987-90. See *Meeting Rural Pumping Needs in Sudan: An Analysis of Pumping System Choice (Diesel, Wind, or Solar)*, J. Hodgkin and R. McGowan, ARD, 1991.

mersibles, vertical turbines, floating suction, and surface-mounted suction pumps) are shown in Figure 13.

Figure 13. Typical Solar Pump Designs



from Kenna and Gillett 1985

6.1.1 The Power Source

PV modules produce a certain current and voltage under specified sunlight conditions. While several types of PV cells are commonly used (e.g., single crystal, semicrystalline, and amorphous), nearly any power module can be employed in a pumping system. Motors used in solar pumping systems have specific electrical characteristics chosen to match those of the array. This increases the overall system efficiency, so more water is delivered per dollar invested in the system. The matching of motors and arrays no longer presents significant problems with standardization among different manufacturers' equipment, since most currently available PV modules have similar electrical output.

Arrays can be wired to produce a wide range of electrical output. Modules are connected in series (i.e., with the terminals minus to plus and plus to minus) to increase voltage (just as you would in a flashlight) and, hence, motor speed at a constant current. Wiring modules in parallel (with terminals minus to minus and plus to plus) increases the current and motor torque at a constant voltage. Motors are designed to operate most efficiently at a certain current and voltage, so a motor with particular electrical characteristics is selected to match the array to get the best system performance. Similarly, the motor must match the characteristics of the pump to use power efficiently. Equipment buyers usually need not match components themselves, as this is handled by PV module and pump manufacturers and system designers. However, because of the importance of correctly matched components, the procedures necessary to do this are included in this manual. This will allow you to confirm specifications given by suppliers.

Equipment distributors specify the array size and configuration (i.e., wiring arrangement for a specific current and voltage combination) needed to pump a certain quantity of water from a given head, based on manufacturer's recommendations. Array sizes are given in term of peak watts (W_p), indicating the array's expected power output under peak operating conditions (defined as 1 kW/m^2 solar radiation on the array and an operating temperature of 25^o Centigrade). Typical power modules are rated at 40 to 60 W_p[3]. The output of PV modules varies depending on the operating temperature and level of solar radiation—i.e., the solar energy per unit of area in watts per square meter (W/m^2). The higher the solar radiation level on a PV cell, the higher the power output. The higher the operating temperature, which depends on the ambient air temperature, the lower the output.

PV pump designs can be varied by adding one or more of the following components:

- **Controllers.** Their functions include regulating current and/or voltage from the array and to the motor, shutting down the motor for various safety reasons, and controlling the system by means of a float switch that turns the motor off when the storage tank is filled.
- **Inverters.** They change the array's electrical output from DC to AC.
- **Power-point trackers.** They convert sunlight into usable electricity more efficiently.
- **Batteries.** They provide a constant voltage to the motor and store energy, so the system can pump water even when the array is unable to deliver enough power directly.

[3] For example, under good sunlight (defined later), an array of 25 modules of 50 W_p each would pump about 30 m^3/day at 20 meters head.

- **Sun-tracking devices.** These move the array so it is directly perpendicular to the sun, thereby intercepting more radiation and increasing the power output.
- **Safety devices.** They prevent damage to equipment if certain problems occur.

Several types of controllers are used with PV pumps, including inverters, power-point trackers, and battery-charge controllers. The PV array produces DC electricity. Some solar pump motors operate directly on DC, others require AC. An inverter is used to convert DC power from an array into AC power for the pump motor. An inverter can also act as a controller to shut down the motor before overloading or overheating occurs, and can help the motor and array operate efficiently in other ways.

Solar cell operating characteristics depicted as current-voltage (I/V) curves are shown in Figure 14. They show a certain current and voltage output for the module under various radiation levels. There is a particular point on an array's operating curve at which it produces maximum power—the maximum power point. A device called a maximum power-point tracker (MPPT) operates the array and motor at or near this point. For example, at a radiation level of 1,000 W/m^2 and an operating temperature of 47°C (the dotted line on the graph in Figure 14), the module shown has a maximum power point at 14 volts and 3 amps. An MPPT does not make a PV array physically track the sun (see below). Using an MPPT makes a system more complex and adds to the cost, but under certain circumstances, it can be a cost-effective means for producing additional power from an array.

Figure 14. PV Module Operating Characteristics

Power Specifications*

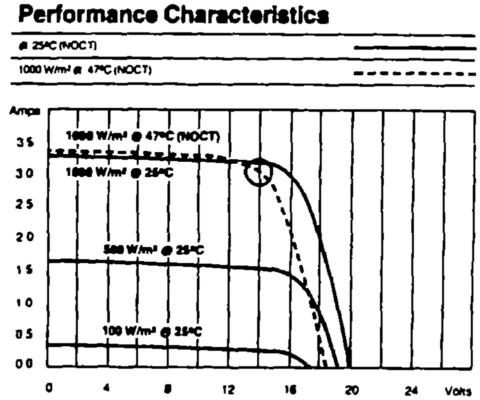
Model	**M75**
Power (typical ± 10%)	**47.0 Watts**
Current (typical at load)	2 94 Amps
Voltage (typical at load)	16.0 Volts
Short Circuit Current (typical)	3.27 Amps
Open Circuit Voltage (typical)	19 9 Volts

Physical Characteristics

Length	48 in/1219 mm
Width	13 in/330 mm
Depth	1.4 in/36 mm
Weight	11 6 lb/5 2 kg

*Power specifications are at standard test conditions of: 1000 W/M², 25°C cell temperature and spectrum of 1 5 air mass.

Performance Characteristics



The IV curve (current vs. voltage) above demonstrates typical power response to various light levels at 25°C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47°C.

Source: ARCO (now Siemens) Solar

Batteries are sometimes used with PV systems as storage devices and/or simple controllers. Solar radiation is intermittent due to variable cloudy conditions and the sun's movement across the sky during the day. Batteries store electrical energy from the array, which can then be used by the motor to run the pump when solar radiation is inadequate to run the system directly. In addition, batteries can serve as controllers to provide constant voltage to the motor, so it operates at a constant speed and higher average efficiency. The disadvantages of batteries include additional cost, higher maintenance requirements, and periodic replacement costs.

Solar radiation is strongest (and PV output greatest) when the incoming solar radiation is perpendicular to the plane of the array[4]. Several kinds of sun-tracking devices can be used to move an array so that it is perpendicular to the sun's rays all day long. These vary considerably in terms of complexity, reliability, and cost. Under certain conditions, array trackers have been shown to produce increases in array output of up to 40 percent over the course of a day. This net gain must be weighed against the increased complexity and cost of these devices in deciding whether to use a tracking array.

Particularly in areas where well yields are low and drawdowns high, or where water tables vary considerably due to drought or unusually heavy use, safety devices (such as low-water cut-out switches and motor overheating/overloading protection) should be included in a pumping system. Some commercial PV pumps are already equipped with these safety devices, but you should request that they be included in any quotation on the price of a system. PV systems should also be properly grounded to protect them from lightning—this inexpensive safety measure should <u>never</u> be overlooked.

All of the controlling and storage mechanisms briefly described here have advantages and disadvantages in terms of their complexity of operation and repair, their effects on system efficiency, and their costs. The emphasis in pump design and component selection should be on trying to achieve long-term reliability instead of the highest possible system efficiency. Reliability has often been shown to be a strong function of a system's design simplicity.

6.1.2 The Motors

Several types of motors are used in solar pumping systems, including DC motors with or without replaceable brushes and AC motors with inverters. DC motors normally use brushes to conduct current to their rotors. These brushes must be replaced occasionally when they are worn down. This poses no problem for surface-mounted motors that are easily accessible for maintenance (if the replacement brushes are locally available). For submersible pumps, however, where the motor and pump are mounted underwater as an integral unit, changing the brushes requires that the entire pumpset and drop pipe be pulled from the borehole, which can be a major operation. Some manufacturers (e.g., A.Y. MacDonald in the United States) use brushless DC motors with submersible pumps. This innovation reduces recurrent costs for periodic maintenance of submersible pumps, since the brushes will not have to be replaced on these units.

[4] At weather stations, solar radiation is usually only measured in a horizontal plane. However, if a PV array is mounted horizontally, it will not intercept the maximum amount of radiation available. In fact, arrays are usually mounted at an angle to the horizontal about equal to the latitude of the site. To determine how much solar radiation hits the *tilted* array, see the discussion of tilt factors in Appendix G.

6.1.3 The Pumps

The most common types of pumps used in PV systems are listed below. Their operating characteristics, typical applications, advantages, and disadvantages were discussed in Chapter 4. These pumps are listed again here with the names of all major suppliers who provide pumps for PV systems:

- ·lf-priming centrifugal—AEG and A.Y. MacDonald;
- submersible centrifugal—Grundfos, A.Y. MacDonald, AEG, Totale, and Hydrosol;
- positive-displacement, reciprocating-piston (jack)—JADCO and Lamb;

Less common types include:

- positive-displacement, rotary—Mono, and Robbins Meyers/Moyno;
- jet—A.Y. MacDonald; and
- vertical or deep-well turbine—Apollo Energy and Pompes Guinard.

In general, PV systems that require high flows for low heads (e.g., for micro-irrigation) use surface-mounted, self-priming centrifugal pumps because of their high capacity, reliability, and ease of maintenance. Submersible units (which are by far the most common), positive-displacement pumps (piston and rotary) and vertical turbines are used for deeper wells and boreholes. Piston pumps are typically high-head, low-flow units. Jet pumps are used for moderate head and flow applications, but are not common.

6.2 Operating Characteristics

The amount of water output for a PV pump depends on the intensity of solar radiation falling on the PV array, the total pumping head, system efficiency, and the operating temperature of the array. Higher radiation levels produce greater electrical output and, consequently, more water. As is true for all pumping systems, the greater the pumping head, the lower the water output for a given power level. An array's electrical output and a pump's water output drop off as the operating temperature increases—thus, PV pumps are more efficient in cooler climates.

Solar radiation varies in several ways:

- daily—as the sun rises and sets and as short-term weather patterns cause cloudy or partially cloudy conditions. Cloudiness reduces solar radiation on the array, sometimes to the point where no water can be pumped unless the system has a battery bank for electrical storage;
- seasonally—as varying long-term weather patterns occur over the year (e.g., monsoons[5] or dry seasons) and as the angle of declination changes (i.e., the angle between the sun's rays

[5] In some places such as India and Malaysia monsoons can obscure nearly all usable solar radiation for up to several months each year.

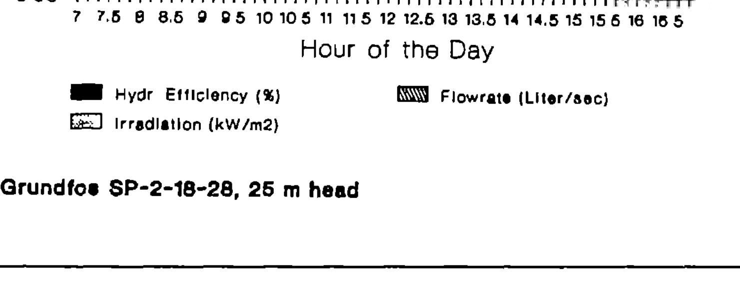
and a horizontal surface on the earth), which is reflected in the sun's lower position in the winter sky and higher position in the summer;

- annually—as weather patterns associated with drought conditions, clouds, air pollution, and monsoons vary; and
- geographically—as a function of latitude and microclimatic weather conditions (e.g., local ground fog and dust storms) at the site.

A typical operating day for a solar pump is depicted graphically in Figure 15, which shows actual measured data for a solar pump on an average sunny day in Botswana. The graph indicates the hydraulic or subsystem efficiency (also sometimes called "wire-to-water" efficiency). This is the ratio of hydraulic energy out of the subsystem (the volume of water pumped at a certain head) divided by electrical energy into the subsystem, the flow rate in l/sec, and the solar radiation intensity[6] in W/m^2. The figure shows how the pump does not turn on immediately in the morning, but only when the cut-in or threshold radiation level is reached (in Figure 15, the cut-in radiation level is about 300 W/m^2). This is the minimum level of radiation at which the array produces enough current to overcome the starting torque of the pump and motor. It varies with the system and site, but higher heads always mean higher starting torque. A similar system is shown in Photograph 5.

Figure 15

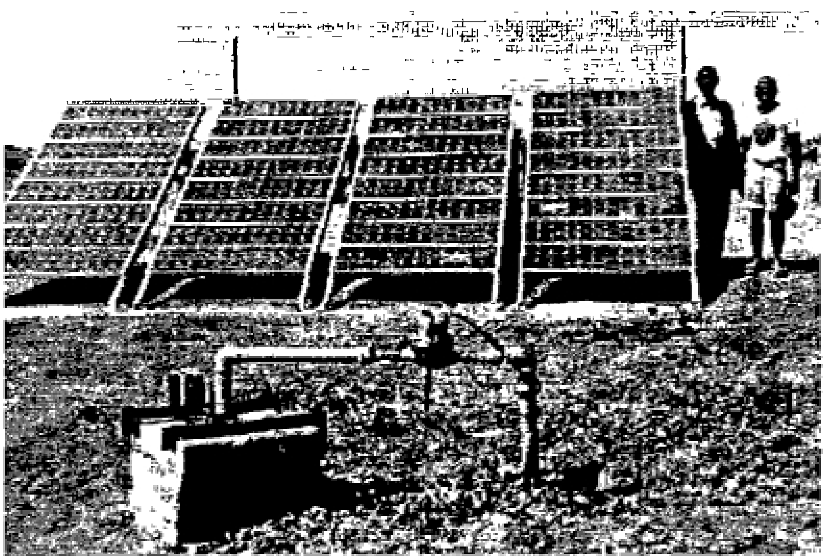
Solar Pump Operating Curves
(on a cloudless day in Botswana)



•Grundfos SP-2-18-28, 25 m head

[6] All figures given for solar radiation in this chapter are radiation levels as measured perpendicular to the array. For tilted arrays, the horizontal value must be multiplied by the "tilt factors" discussed in Appendix G.

Photo 5.



Grundfos submersible solar pump for village water supply in Botswana

For poorly designed systems, the cut-in radiation level may be so high that the pump runs for only a short period during the day or may not turn on at all. By using certain types of controllers (e.g., MPPTs), the system's cut-in radiation level can be lowered so it operates for a longer period each day. Similarly, for days with low radiation (for example, a very cloudy day), even a well designed system may never reach its cut-in radiation level and, hence, will not operate that day.

After the cut-in level is reached, the pump turns on and the flow rate increases until around noon when the sun is at its highest point in the sky. Thereafter, solar radiation and, consequently, pump output decrease until the cut-out radiation level is reached in late afternoon and the pump stops. As you can see from Figure 15, the system's hydraulic efficiency increases early in the day until the unit is in its normal operating range (about 32-34 percent), levels off, and then drops off again in the late afternoon.

Because of the variability in solar radiation and the consequent variability of pump output over a given period, solar pumps (like wind pumps) require some type of storage system so that water is always available to users. For PV pumps, energy can be stored either electrically (using batteries) or hydraulically (water in a storage tank). Considerable debate has taken place on battery versus water storage, as well as on the amount of each required for any given installation. A general rule of thumb is that systems should be designed with three days of storage. The type of storage depends upon several factors, primarily the local cost and availability of storage tanks and batteries, and secondarily the likelihood that batteries will be properly maintained. Storage tanks require considerably less active maintenance than batteries, and so are less likely to fail over the long run. Batteries in PV pumping systems often are not serviced properly, and thus must be replaced frequently at considerable expense.

One of the best features of solar pumps is that their normal operating requirements are minimal compared to most other types of systems. A solar pump usually operates completely automatically, so pump operators are not strictly required (as they are with diesel engines, for example). Also, solar pumps do not require fuel.

6.3 Choosing a Solar Pump

Sizing methods for solar pumping systems range from very simple to highly complex. This section shows a simpler method first, and then a more complex and accurate one.

6.3.1 Calculating Power Requirements

The simplest sizing method calculates the power required, given the estimated head and flow rate. Remember that subsystem efficiency is the ratio of energy out of a system (i.e., water flow for a given head) divided by energy into the system (electrical energy output from the array). Using a typical subsystem efficiency of 30 to 40 percent[7], the necessary array size can be estimated quickly.

The actual power required to pump water is defined as:

$$P_{req} = \frac{(9.81 \times H \times Q)}{\eta_{sub}}$$ **Formula #8**

where P_{req} = power required in watts

9.81 = gravitational constant

H = total pumping head in meters

Q = flow rate in liters per second

η_{sub} = subsystem efficiency of 0.30 to 0.40

Example 9: Power Requirements

To pump one liter per second (l/sec) against 28 meters head for a system with a subsystem efficiency of 30 percent, what is the electrical output needed from an array?

$$P_{req} = (9.8 \times 28 \times 1)/0.30 = 915 \text{ watts}$$

7 Manufacturers' literature usually quotes this efficiency as measured under ideal conditions, as high as 50 to 60 percent. Our field measurements of the subsystem efficiency of many installed solar pumps, including motor, pump, and controller, have never been higher than 40 percent.

Since energy equals power times time (in hours), if a pumpset ran for two hours at that rate, *energy* consumption would be 915 watts multiplied by two hours, which is 1,830 watt-hours or 1.83 kWh. This is the hydraulic energy demand discussed in Chapter 3. The next step is to determine the size of array in W_p that could supply the 915 watts of power under peak solar radiation conditions.

Example 10: Approximate Array Sizing

For the system in Example 9, assume that ARCO/Siemens Solar M-53 modules are used in the array. Each typically produces about 2.2 amps of current at 15 volts when driving a pump under 1,000 W/m^2 of solar radiation (from the manufacturer's literature). The required motor voltage is 105 volts (for a Grundfos submersible pump). How should the array be wired, and how many modules should be used?

Since wiring modules in a series increases voltage, the motor voltage of 105 is divided by the module voltage of 15, so that 7 (7 x 15V = 105V) modules must be wired in series to produce the required voltage. Together, those seven modules have an output of 105 volts multiplied by 2.2 amps, or 231 watts. The modules connected in series are called a "string." Dividing the system's overall power requirement (915 watts) by the output of each string (231 watts) shows that four strings of seven modules are required, or a total of 28 modules.

The solar array in Examples 9 and 10 only produces 915 Watts when the solar radiation level is 1 kW/m^2. For many places, this is the highest level reached during a good sunny day. Remember that this is an instantaneous *power* level, and that *energy* is power per unit time. In weather data, solar radiation is usually given in energy units of kWh/m^2-day. The solar energy level on a good sunny day at low latitudes can reach 6-7 kWh/m^2-day. The power level, however, varies over the day, starting out low in the morning, peaking around mid-day, and then dropping off to zero as night falls. A quick estimate of solar pump water output over a day is to calculate its output at 1 kW/m^2 (solve for "Q" in Formula 8), then multiply that instantaneous output by the number of "peak sunlight hours" in an average day (e.g., 6 if the solar radiation level is 6 kWh/m^2-day) to get:

6 hrs/day x 1 l/sec x 3,600 sec/hour = 21,600 l/day = 21.6 m^3/day

This rough method of system sizing oversimplifies the real situation in several ways:

- The level of solar radiation actually varies continually over the course of a day—starting at zero, radiation increases to its maximum about noon and then drops off to zero again after sunset.
- System efficiency varies with radiation level and temperature—efficiency improves as radiation increases (up to a point; again see Figure 15) but drops as the temperature rises in the afternoon.
- It is assumed that all of the 6 kWh/m^2day can be used by the system—in fact, for systems without batteries, radiation below the cut-in level is wasted because the pump is not running.

However, since the method can be used to estimate a maximum flowrate, it is used to calculate head loss in piping (see Example 12). This method is, however, useful for calculating motor power requirements, and the wiring scheme for the array.

6.3.2 More Accurate Array Sizing

A somewhat more accurate way of estimating the size of the solar array needed to pump a given amount of water is to use the following formula:

$$\text{Array Size in } W_p = \frac{9.81 \times H \times Q_D}{H_t \times 3.6 \times F_m \times F_T \times \eta_{sub}} \qquad \textbf{Formula \#9}$$

where W_p = peak watts

9.81 = gravitational constant

H = total pumping head in meters

Q_D = desired daily water output in m^3/day

H_t = global solar radiation *in the array plane* (kWh/m^2day)

3.6 = conversion factor (kWh to MJ)

F_m = array/load matching factor, 0.9 for centrifugal pumps, 0.8 for others

F_T = de-rating factor for operating temperature of array output cells (0.8 for warm climates and 0.9 for cool)

η_{sub} = subsystem efficiency

This formula better approximates the actual operation of a solar pump, except that it does not take into account the cut-in and cut-out radiation levels, mentioned above, below which the pump will not operate in the early morning and late afternoon. However, these are relatively small errors which tend to overestimate the daily output by 5 percent or so[8]. Virtually every variable except array size and the gravitational constant changes with the time of day and the season. The array/load matching factor is a measure of the electrical impedance mismatch between a PV array and the subsystem load (i.e., the subsystem controller or pump motor in a direct-coupled system). An example of how to use this formula is given in Example 11.

To simplify the process of sizing a PV system, Table 4 shows the array size needed to pump a given amount of water (10 to 30 m^3/day) at a given head (10 to 60 meters) for three different radiation levels. The array sizes were computed with the Formula #9 above for more accurate array sizing, using values for a centrifugal pump in a warm climate.

[8] In fact, you can incorporate this into the calculation by using an "average daily subsystem efficiency." This can be approximated by taking the efficiency at noon (about 32-34 percent) and multiplying it by 0.95 to get the average daily efficiency, which will take into account energy losses before reaching the cut-in level, and after reaching the cut-out level.

Example 11: More Accurate Array Sizing

Use the more accurate formula given above to calculate the size of the array needed to pump 20 m^3/day from 28 meters of head, using the equipment described in Examples 9 and 10.

$$\text{Array Size in } W_P = \frac{9.81 \times 28 \times 20}{6 \times 3.6 \times 0.9 \times 0.8 \times 0.30} = 1{,}177 \; W_P$$

where

gravitational constant = 9.81

H (pumping head) = 28 meters

water output = 20 m^3/day

solar radiation = 6 kWh/m^2day)

conversion factor (kWh to MJ) = 3.6

F_m = 0.9

F_t = 0.8

η_{sub} = .30

A 28-module array (one module = 43 W_P) would be adequate here. Using the procedure in Example 10, you could then calculate the number of modules connected in series and parallel to give the required motor volts and amps.

6.3.3 Summary of Solar Pumping System Design

To design a cost-effective system properly, historical data on local solar radiation conditions should be used, where available. Unfortunately, such information is seldom collected in many areas of most developing countries. Thus, estimates of monthly radiation levels over the year must be used. Possible sources of local radiation data (e.g., meteorological data and PV manufacturers' world or area maps) are discussed in Chapter 2. The average daily radiation level used in array sizing should be based on the design month. The concept of design month for solar pumps is similar to that for windmills—it is the month in which it will be most difficult to meet the water requirement at the site given the available solar energy.

When drawing up bid documents for solar pumps, specify the water requirement as a certain average daily amount at an estimated total pumping head (including expected friction losses), and supply whatever local radiation data are available. When reviewing dealers' quotes, use the example given below to check that the systems being proposed are reasonably sized to meet the water demand at the site. Bidders' estimates of water output should be within 15 percent of your calculations from the method described here. Otherwise, the system being proposed will probably be improperly sized to meet your requirements.

Table 4. Sample Solar Pump Sizing Table

Array Size (Watts Peak) to Pump Given Volume at Given Head
(Subsystem efficiency = 30%, and radiation of 4, 5, and 6 kWh/m^2day)

	Water Demand (cubic meters per day)								
	10			20			30		
	Solar Radiation (kWh/m^2day)								
Head (m)	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
10	315	252	210	631	505	421	946	757	631
20	631	505	421	1,262	1,009	841	1,892	1,514	1,262
30	946	727	631	1,892	1,514	1,262	2,839	2,271	1,892
40	1,262	1,009	841	2,523	2,019	1,682	3,785	3,028	2,523
50	1,577	1,262	1,051	3,154	2,523	2,103	4,731	3,785	3,154
60	1,982	1,514	1,262	3,785	3,028	2,523	5,677	4,542	3,785

For example, to pump 20 cubic meters per day at 30 meters head given a 30 percent subsystem efficiency, if your solar radiation level is 6.0 kWh/m^2day, then you would need a 1,262 Watt peak array (rounded up to the nearest commonly available size).

If you decide that you want to use batteries with your system, either because of a low yield borehole or to increase water availability, a more complex procedure is required.[9]

The following example illustrates the complete procedure for sizing a solar pump and its components.

[9] See the section on PV water system design in *Stand-Alone Photovoltaic Systems, A Handbook of Recommended Design Practices*, Photovoltaic Design Assistance Center, Sandia National Laboratories, Albuquerque, New Mexico.

Example 12: Detailed Solar Pump System Selection

A solar pump is being considered for use at a village site in rural Sudan, where an elevated tank (5 meters high) stores water pumped from a nearby borehole. The distance from the borehole to the storage tank in the village is 250 meters. The borehole currently has a 6-inch diameter casing. It has been test-pumped for 72 hours by a local drilling contractor, and a yield of 5 m^3/h was measured. The depth from the top of the borehole to the water surface during the test-pumping was 13 meters. Radiation on a solar array during the design month is 6 kWh/m^2day (or 21.6 MJ/m^2day). The village currently has 680 people, and the sheikh estimates that the population increases by about 2 percent annually. Currently, people use about 30 liters each per day. The availability of diesel fuel has been so irregular and its price has been increasing so rapidly that the community is considering buying a solar pump with an agricultural development bank loan. Size an appropriate system for this community.

First, determine water demand. The current population of 680 is growing at 2 percent per year (F_{PG}). The system should be sized to provide an adequate supply of water over its entire useful life (N), which is expected to be 20 years (some components will have to be replaced as not all of the equipment will last this long). From Formula 1 in Section 2.1.3, the demand in year 20 will be:

$$\text{future demand} = (\text{current demand}) \times (1 + F_{PG})^{(N-1)}$$

$$= (680 \text{ people} \times 30 \text{ l/day}) \times (1 + .02)^{(20-1)}$$

$$= 30 \text{ m}^3\text{/day}$$

Second, determine total pumping head. Begin by calculating friction losses. The average pumping rate can be estimated by assuming that the 30 m^3/day output requirement will be pumped over 6 "peak sun-hours" (6 kWh/m^2day), so the peak flow rate will be:

$$(30 \text{ m}^3\text{/day})/(6 \text{ peak sun-hours/day}) = 5 \text{ m}^3\text{/h} = 1.4 \text{ l/sec}$$

You intend to use a submersible pump with a 50-millimeter galvanized iron drop pipe in the borehole. The pump will be set 5 meters below the dynamic water level to keep the pump wet and properly cooled. The total length of piping in meters will be:

13 (borehole) + 250 (pipe run) + 5 (pump set) + 5 (tank) = 273 meters

From Figure 4 (in Chapter 2) and the tables in Appendix B, the friction loss under these conditions--273 meters of 50-mm galvanized steel pipe with negligible losses due to bends and valves--is 3.6 meters. The total pumping head would then include the dynamic head of 13 meters, the discharge head to the elevated unpressurized tank of 5 meters, and friction losses in the pipes of 3.6 meters for a total of 21.6 meters.

Note that the 3.6-meter friction loss is greater than 10 percent of the total head. Therefore, you should use slightly larger pipe to reduce the friction loss (thereby reducing the amount of energy required to pump your water). With 65-millimeter pipe, the friction loss is 1 meter. The total head is then 18 + 1 = 19 meters.

(continued next page)

Example 12: Detailed Solar Pump System Selection ***(continued)***

Third, determine the array size needed. Follow exactly the same procedure as given in Example 11. Use a subsystem efficiency of 32 percent, which is typical of Grundfos submersibles available in Khartoum, and a water demand of 30 m^3/day for 19 meters of head. You can now compute the array size needed from Formula #9:

$$\text{Array Size in } W_P = \frac{9.81 \times 19 \times 30}{6 \times 3.6 \times 0.9 \times 0.8 \times 0.32} = 1{,}124\ W_P$$

This figure is the minimum array size in W_p that can meet your water requirement. However, other requirements must be taken into account. The Grundfos submersible you are looking at runs at 105 volts. You are considering using Solarex modules, specifically the MSX-53 version on which a dealer in Khartoum has given you a quote. These 56 W_p modules have a typical operating voltage of 15 volts. This means you will have to wire 105/15 or seven modules in series to get the right voltage.

Finally, to find the total number of modules, divide 1,124 W_p by 56 W_p per module or about 21 modules (rounding up to the nearest multiple of seven). Your array would then be wired as three parallel sets of seven modules each. This system size should match the one described in the dealer's quote. To select the individual pump set, review the pump curves for the types of submersibles the dealer carries, and pick the unit that operates most efficiently at the head for your site (19 meters). Since you are using Grundfos units, your best choice is probably the SP8-4. Your system sizing is now complete.

6.4 Cost Considerations

Solar pump costs depend primarily on two components—the array size and the pumping unit. Solar module costs usually make up 60 to 85 percent of the total system cost (a higher percentage the smaller the system, since the balance of the system is a fixed price) and are usually quoted in terms of dollars per W_p or US\$/W_p. In 1983, module costs were about US\$10/W_p, shipped from the country of manufacture. In 1992, they were being quoted as low as US\$5/W_p to US\$6/W_p. The larger the system, the higher the proportion of system cost that is represented by PV modules. These prices usually do not include freight and insurance charges to ship to developing countries, which can easily add 50 percent or more to the price. For example, in 1988 modules with a U.S. price of \$5/W_p were quoted in Botswana for \$8/W_p. Pumpsets (i.e., a pump and motor) designed for use with PV systems range in price from US\$500 to US\$2,000 (FOB the manufacturer), with the units rated for lower power output costing less and often used at lower heads (e.g., surface-mounted centrifugal and jet pumps). Units with higher power output for deeper wells run from US\$2,000 to US\$3,000. Submersible AC pumps are generally the most expensive because in addition to the pump and motor, they must have an inverter to convert DC power to AC. Often, the higher cost (US\$2,750) of these units is more than offset by greater reliability and, consequently, lower recurrent costs.

Other costs associated with solar pumping systems include the array mounting structure, wiring, other types of controllers, water meters, civil works (e.g., a concrete pad for the array and piping), and storage tanks. These costs can vary considerably depending on whether the equipment and/or materials are made locally or imported. Check with local dealers for estimates of these costs. Typical costs for each component are given in Table 7 in Chapter 10.

6.5 Maintenance and Repair

While normal operating procedures for PV pumps usually require minimal user support, they do need some attendance. Dust should be washed from the collector array as required (i.e., when it is obviously coating the modules), and for surface-mounted motors, belt tightness and any overheating of the motor or transmission should be noted. If float switches are used in the system's storage tank, they should be checked periodically for proper operation. Water output should be recorded by reading the flow meter on a daily basis. This will permit a more rapid diagnosis of any problems occurring with the system.

One person (preferably from the community served by the pump) should be assigned the responsibility of monitoring pump operation, recording water-use data, and determining the nature and extent of any breakdowns that occur. This individual could be trained to deal with simple repairs, such as loose or broken wires. He or she should also know exactly how to call for a repair crew if repairs are required. Because of the complexity of most of the components in PV pumping systems, it is much more likely that the first response to breakdowns will be to replace a component rather than to make an on-site repair.

In some circumstances, particularly at unattended or remote sites, vandals or animals may break the modules or rip out the wires. Qualified personnel performing periodic maintenance should check for this, and should also check for natural degradation such as corroded terminals and worn insulation. The equipment should *definitely* be fenced in to protect it from children and animals and to protect them from electric shock. Animals can easily shut down an unprotected system by scratching themselves on the array's mounting supports and knocking them over or by chewing through the insulation on wiring and short-circuiting the system. Representatives from user groups should be chosen and charged with notifying repair crews promptly so that any necessary repairs can be accomplished quickly to minimize downtime.

PV pumps require little maintenance during most of their useful lives. However, like any other piece of equipment, they do require some periodic care. The type of maintenance depends on the type of system. DC motors require periodic brush replacement unless they are brushless. Pump seals fail and must be replaced occasionally. Belt-driven pumps must have the belts tightened and eventually replaced. For piston pumps, the cylinder cup leathers must be replaced about every 12 to 24 months. When pumping water with fine sand (e.g., in Sudan or Somalia), leathers may have to be replaced as often as every six months.

Maintenance problems will be worse when systems are installed on low-yield wells, in water sources that have wide fluctuations in water level, or where the water quality is marginal. If low-water or overheating cut-off switches are not used, down-hole equipment, including pumps and motors, can be destroyed when water levels drop below the depth of the pump installation. Under very low-flow conditions where the pump continues to operate, an insufficient flow of water past a submersible pump may not provide sufficient cooling and may damage the pump.

For properly designed systems, monthly or bimonthly maintenance consists of visually inspecting electrical connections, tightening nuts and bolts, cleaning the array, checking the array electrically (on a quarterly basis) to make sure it is working properly, and checking the battery bank, if there is one. This should take no more than one to two hours of a mechanic's time, not including any required travel.

Most problems in PV pumping systems occur with components other than the array. Unless they are vandalized, modules very seldom fail. If they are severely damaged, they may have to be replaced, at great expense (US$250 to US$350 each). It is much more cost-effective to educate users about the importance of teaching children and others not to damage the water supply system.

Most problems occur with the pump, motor, and controller. Generally, the design philosophy behind solar pumps has been to manufacture components that will be replaced rather than repaired, at least for most situations in developing countries. Dealer representatives for U.S. or European PV pump manufacturers are usually assigned only to developing countries with large numbers of solar pumps or at regional centers such as Nairobi in East Africa. They often carry spare parts for pumps (e.g., impellers and seals) or will replace the unit if it is under warranty.

Motors are more problematic. Depending on the level of technical skills in your area, electric motors can be rewound locally. Local mechanics or mechanically-inclined users can easily replace the brushes, if the motor is easily accessible. Local mechanics can also replace pump or motor seals, assuming that similar types of equipment are used locally (e.g., grid-electric submersible pump sets). With the exception of brush replacement, most procedures should be carried out in a clean electrical shop in the nearest large town, rather than in the field.

Of course, appropriate spare parts must be available. If not, considerable time and effort may be required to find the necessary parts locally or to have them shipped from the manufacturer. The importance of a complete spare parts inventory cannot be overemphasized. The biggest problem in system maintenance and repair is the time it takes to address the problem from abroad. When choosing a supplier, remember the importance of local dealers who maintain supplies of spare parts and can fix or are willing to replace failed or defective equipment.

There is little, if any, local manufacture of PV pumping equipment in developing countries[10]. Battery-charge controllers are made in some developing countries, and the number of Spire Corporation's turnkey PV cell and module assembly plants in the developing world is slowly increasing. Given the highly automated and sophisticated manufacturing techniques that are typically used to make PV equipment, all of it will probably be imported in most developing countries over the near term. In many countries, there are simply no local dealers. In countries those with local dealers, their knowledge of the product and proper system design procedures may be minimal, so potential customers must either have access to design guidelines (such as this manual) or look elsewhere for equipment. If this is the case in your area, you might reconsider the possibility of using systems that are already available locally. In some countries, knowledgeable, well-equipped dealerships can provide accurate system design, prompt procurement from existing inventories or as a result of good relations with manufacturers, and trained crews for installation and user training. At present, this type of situation is the exception rather than the rule.

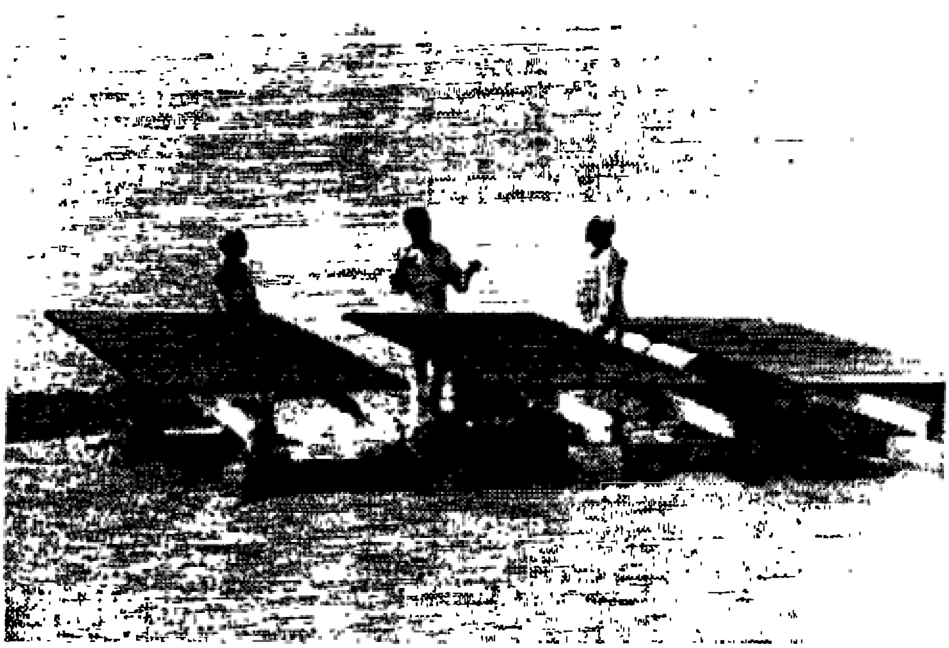
[10] However, modules are now manufactured in countries such as India and China.

6.6 Equipment Life

Since PV pumps are a relatively new technology (compared to diesel engines, windmills, and handpumps), little is known about the economic lifetime that users can reasonably expect of most systems and components. While field tests have been conducted for certain types of systems, few PV pumps have been in actual use for more than ten years (as of 1992). Module manufacturers now commonly guarantee their products for 10 years against significant loss of power output, and accelerated tests have indicated that modules will retain up to 90 percent of their original power-generating capacity for up to 20 years after the initial installation. The need for module replacement because of damage is very dependent on the site[11] (see Photo 6).

Other components are not so robust. The motor will probably have to be replaced every three to seven years, depending on the level of operating power (i.e., the higher the power, the sooner the motor will need replacement), the quality of the water (for submersibles, poor water quality tends to corrode casings and ruin seals more quickly), and the quality of the installation. Electronic components, such as controllers, may also need replacement every three to five years, depending on the quality of the equipment. Array mounts should never need replacement.

Photo 6.



A newly installed solar pump in the North Kordorfan region of Central Sudan. If it does not suffer damage from vandalism, the array will probably provide power to pump water for up to 20 years.

11 See Hodgkin and McGowan (1991) for information on module damage for systems in Sudan.

Chapter 7: Windpumps

Wind pumping systems or windmills convert the energy in wind into mechanical or electrical energy to drive a pump. This section covers what you need to know to:

- gather the necessary information to determine whether a windmill will meet the demand for water at your site; and
- select a properly sized windmill and pump if this type of system is appropriate.

Since the vast majority of all windpumps used in developing countries are mechanical windmills driving piston pumps, that type of system is the primary focus of this chapter. Other types of windpumps will be mentioned only briefly.

7.1 System Description

Wind energy systems are generally subdivided in two ways: by rotor axis (horizontal- or vertical-axis machines) and by power type (electrical or mechanical). While it is possible to pump water using the energy produced by any of these four possible configurations, the most common type is the horizontal-axis, mechanical system, which is usually referred to as a steel-bladed, farm-type windmill, or simply a farm windmill. Dempster, Aeromotor, Fiasa, and Southern Cross windmills are examples of this system design. Figure 16 shows a schematic diagram of this type of wind energy system.

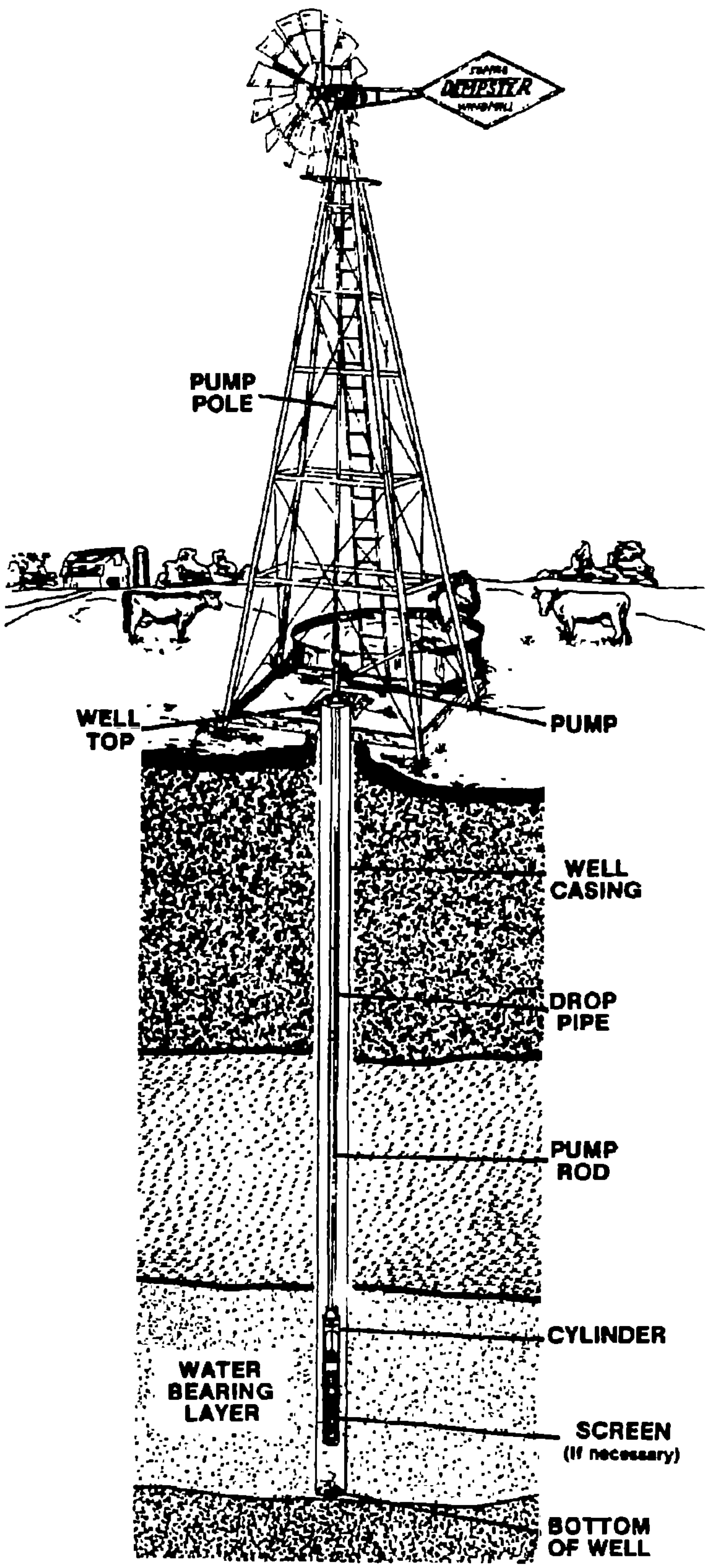
A typical farm windmill has four main parts:

- a horizontal-axis wind wheel, which converts power in the wind into the rotary shaft power of the axis;
- a windmill "head," which changes the rotary motion of the axis to a vertical reciprocating motion and makes any necessary gear reductions;
- a tail attached to the head, which has two purposes—it allows the windmill to track changes in the wind direction and, along with a brake, permits the windmill to be furled (i.e., taken out of the wind and stopped) during high winds or when otherwise desired; and
- a tower (usually steel) on which the windmill head is mounted.

This design is nearly always used with a reciprocating-piston pump. The typical multiblade configuration is designed to provide the required high torque to start the pump at low windspeeds. At higher windspeeds, the efficiency of a system is somewhat reduced due to rotor aerodynamics and load characteristics.

For a fixed windspeed, a windmill's power output is proportional to the diameter of the rotor. Commercial farm windmills vary in diameter from 3.0 to 7.3 meters. Water output depends on the amount of energy delivered to the pump cylinder. Cylinder sizes for reciprocating pumps vary in terms of diameter and length of stroke—the larger the cylinder diameter and the longer the stroke, the more water pumped per stroke. Commonly available cylinders run from 2.25 to 4.0 inches in di-

Figure 16. Typical Windmill Installation



Dempster Manufacturing Literature

ameter, although larger sizes can be obtained if desired. The stroke length is generally determined by the design of the windmill head and is typically 12-24 inches. Towers typically come in heights of 9, 12, and 15 meters. The higher the tower, the greater the amount of energy the windmill can capture.

Recent efforts at improving the design, reducing the weight, and simplifying fabrication procedures have resulted in a new generation of windmills. These differ from traditional designs in many ways, including the elimination of gears and castings, which permits simplified fabrication techniques, and improved rotor efficiency based on a better understanding of aerodynamic design. Photographs 7 and 8 show two examples of new-generation machines.

Another type of windmill that has been tested and demonstrated on a much smaller scale than the farm windmill is the Savonious vertical-axis design. The rotor consists of several curved metal blades mounted around a central, vertical axis of rotation. Initially, this design showed promise as a simple, inexpensive, easily constructed device for utilizing wind energy. However, for water pumping applications, it has not proven effective. It is inefficient; problems have arisen in controlling its speed to protect it from high winds; towers that are strong and large enough to get the rotor up into the wind-stream are quite expensive; and coupling the vertical shaft to a pump that will operate efficiently at the rotor's low rotational speeds has proven difficult.

Other mechanical windmill designs are relatively uncommon, particularly in developing countries. Thus, this section focuses on the steel-bladed, farm-type windmill and recent improvements in its traditional design.

7.2 Operating Characteristics

Water output for a windpump depends on a variety of factors, the most significant being:

- the wind regime at the site;
- the pumping head;
- the diameter of the windmill rotor; and
- the size of the pump cylinder.

The single most important factor is the windspeed at the site. The power available in wind varies as the cube of the windspeed—if the windspeed doubles, the power available increases by a factor of eight. Because of variations in wind regimes (e.g., gusts and variable directions), windspeeds can only be measured and predicted statistically, and water output can only be estimated statistically. There is no guarantee that a specific amount of water will be delivered per day, week, or month. This limits windmill use to applications with flexible water requirements, large storage capacity, or some sort of backup system. Most applications will need a storage tank which can hold enough water for three to four days.

As with any pumpset, the output of a specific windmill/pump combination at a given site is inversely proportional to the pumping head—as the head increases, the output decreases. All other factors being equal, the water output increases as the size of the rotor increases (a larger rotor offers a larger area for wind capture) and the height of the tower increases (winds are faster further from the ground).

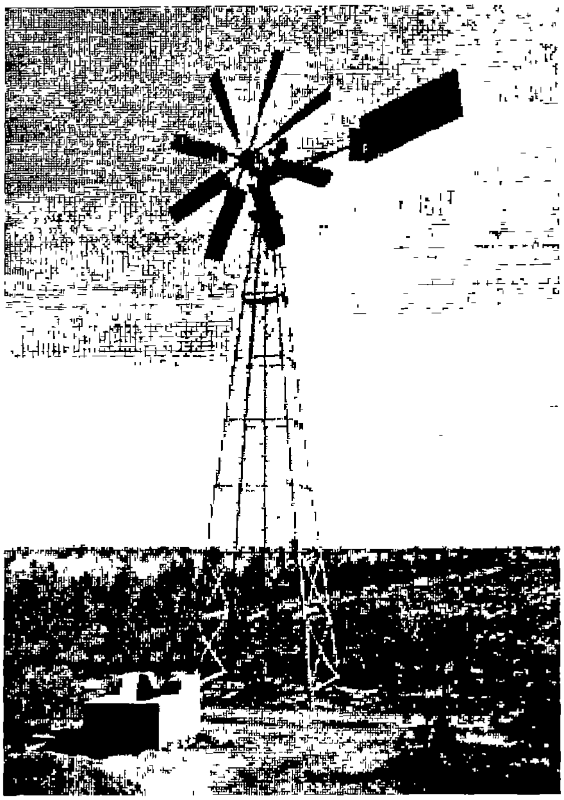
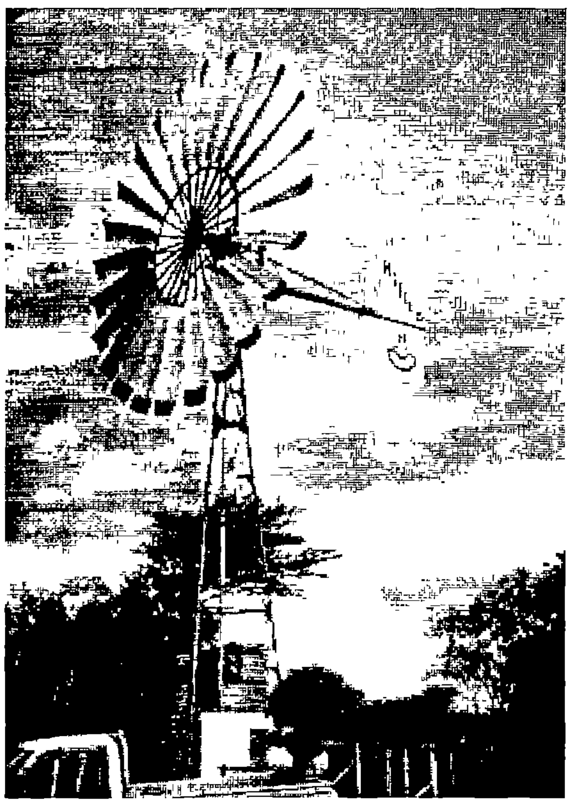


Photo 7.

CWD-5000 Windmill (6 m diameter) for water and micro-irrigation near Khartoum, Sudan

Photo 8.

Kijito 20-foot used for village water supply and stock water in southern Botswana



Rotor sizing is a fairly simple procedure (see Formula 10 below), but selecting a pump cylinder is more complex. A small cylinder will start pumping at lower windspeeds, but does not deliver as much water per stroke as a large cylinder. Larger cylinders require greater power to start pumping, but once started, they deliver more water per stroke. For each combination of windmill, pumping head, and wind regime, there is an optimum point at which a balance is reached between the longer pumping hours required with smaller cylinders and the higher pumping rates for larger ones. At lower average windspeeds (less than 4 m/sec), smaller cylinders are usually selected to maximize total water output.

The relationship between windspeed, head, and amount of water pumped for a given size of windmill is shown in Figure 17. (Photograph 9 shows the windmill on which Figure 17 is based.) The two lines show daily water output in cubic meters for a Climax 12-foot diameter machine and 45 meters of head, using 2- and 4-inch cylinders. For example, at an average daily windspeed of 3 m/sec, the 4-inch cylinder will pump only about 1.6 m^3/day, but the 2-inch will pump about 2.8 m^3/day because the windmill starts the smaller cylinder moving in lower windspeeds. However, in winds that are 4 m/sec and above, the larger cylinder will deliver considerably more water, pumping 8 m^3/day versus only 4.6 m^3/day for the smaller cylinder. This difference increases as the windspeed goes up.

7.3 Choosing a Windmill

In most countries there is not a wide selection of locally available windmills. It is not quite so important to have a local dealer for windmills as it is for diesel engines because windmills require less maintenance; nevertheless, a local source for spare parts is needed. Moreover, if a reputable company manufactures windmills locally in your country or region (e.g., the Kijito in Kenya or the Sanit in Thailand), these makes should be considered first. Windmills are usually procured directly from a manufacturer or its agent. The most common approach is to purchase the windmill and tower directly from the manufacturer and the pump cylinder, rod, and drop pipe from local suppliers. Buying these latter three components locally is preferable since this ensures that if any parts are omitted or incorrectly specified, they can be replaced locally. It is also a good indicator that spare parts and knowledgeable mechanics will be available when they are needed. Finally, purchasing local products for the pump rod and pipe will probably be considerably cheaper.

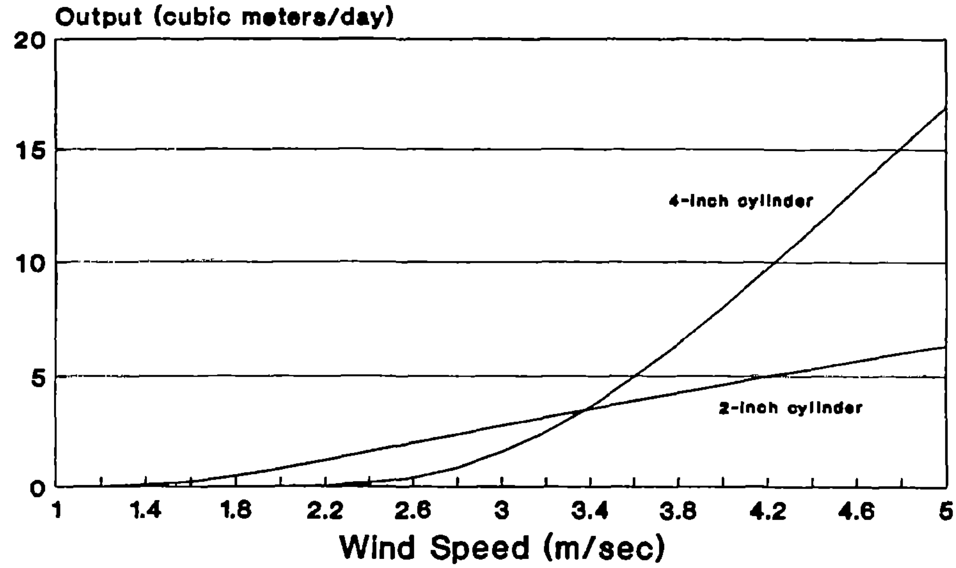
To follow the design procedures outlined in this section, it is not essential to understand all the aspects of the theory behind wind energy use. The general approach in wind system design is to:

- determine windspeeds at the site;
- determine the design windspeed;
- calculate the necessary rotor size to meet the water demand; and
- choose the proper cylinder to maximize water output.

Figure 17

Windmill Output

Climax 12-foot Diameter Rotor*



*45-meter head

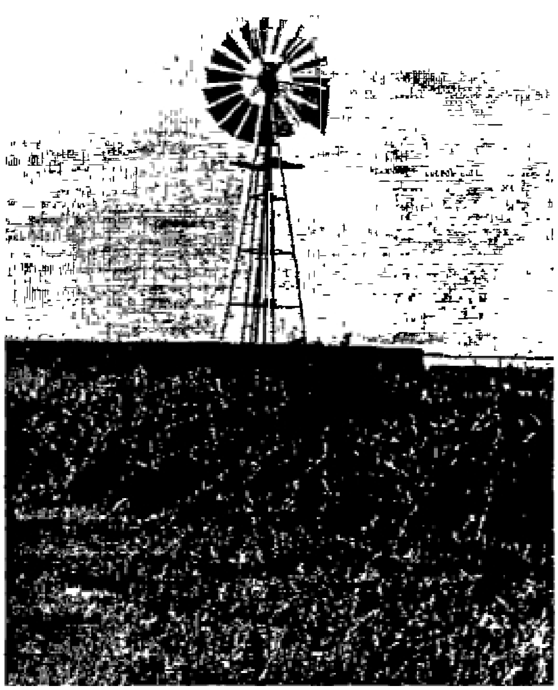


Photo 9.

Climax 12-foot in Botswana used for village water supply and small stock watering

The power available in wind is given by the following formula:

$$P_W = 0.5 \times \rho_a \times A \times V_a^3$$ **Formula #10**

where P_W = power available in the wind in Watts

ρ_a = air density in kg/m^3

A = cross-sectional area of wind being intercepted (i.e., area covered by windmill rotor in m^2)

V_a = windspeed in meters per second (m/sec)

Note that the power in the wind is proportional to the **cube** of the windspeed. This means that **doubling** the windspeed increases the power available by a factor of **eight**. It also means that small errors in estimating windspeed can result in large errors in estimating available power in the wind.

7.3.1 Site Windspeeds

There are two ways to estimate average windspeeds at your site. The first assumes that no wind data have been collected at the site but that long-term data is available from a meteorological station relatively nearby. The second method assumes you have recorded several months of wind data at the site, but have no long-term annual data except for information from a nearby meteorological station. In the first case (i.e., no site data), certain correction factors can be applied to estimate windspeeds at your site from meteorological information:

- a height correction, if the windmill will be at a different height than the recording instruments;
- a correction for local terrain conditions; and
- a correction factor if the data has been recorded over a short duration.

These correction factors (described in detail below) should be used with caution. Because the power in the wind is proportional to the cube of the windspeed, small errors in estimating windspeed can lead to large errors in estimating wind-pump output. Where possible, you should always try to gather at least several months of windspeed data at your proposed site at the actual planned height of the windmill rotor. These short-term data can then be correlated with longer-term data from the nearest meteorological station. Site-specific data will help you more accurately determine whether a windmill is a good investment or only a marginal one.

Wind data are recorded with an instrument called an anemometer, which is basically an electrical switch that counts the rotations of multiple cups or a propeller rotating at a speed proportional to the surrounding windspeed. The number of rotations are counted, multiplied by a conversion factor, and then divided by the time elapsed to give an average windspeed in meters per second (m/sec) or miles per hour (mph).

Anemometers are mounted on poles at a fixed height above the ground, usually 2 or 10 meters. Under normal conditions, windspeeds are greater at higher distances above the ground. This is largely because the effects of surface features and turbulence diminish as the height increases. Windspeed variability depends on the distance from the ground and the roughness of the terrain. Windspeed data should include the height at which the data were collected (i.e., the height of the anemometer). If you plan to use a tower with a different height than the anemometer used to collect the windspeed data, you can use the following formula to estimate the windspeed at the desired height:

$$V_2 = V_1 \times \left(\frac{h_2}{h_1}\right)^{1/7}$$

Formula #11

where V_2 = unknown windspeed at the windmill's height (h_2)

V_1 = known windspeed at the anemometer's height (h_1)

It is much more difficult to predict average monthly windspeeds if the anemometer height at which the data were recorded is less than six meters. If you can avoid it, data collected at heights of less than six meters should not be used to select a windmill or predict performance because of their inaccuracy.

In relatively flat areas with no trees or buildings in the immediate vicinity, site selection is not so critical if you extrapolate windspeed data from another site. However, in mountainous areas or places where obstacles may block the flow of wind, differences in surface roughness and obstacles between the anemometer and pump site must be taken into account when estimating site windspeeds. As a general rule, a windmill tower should be tall enough so that the lowest part of the rotor is at least 9 meters off the ground or 5 meters above any obstruction within a radius of 100 meters.

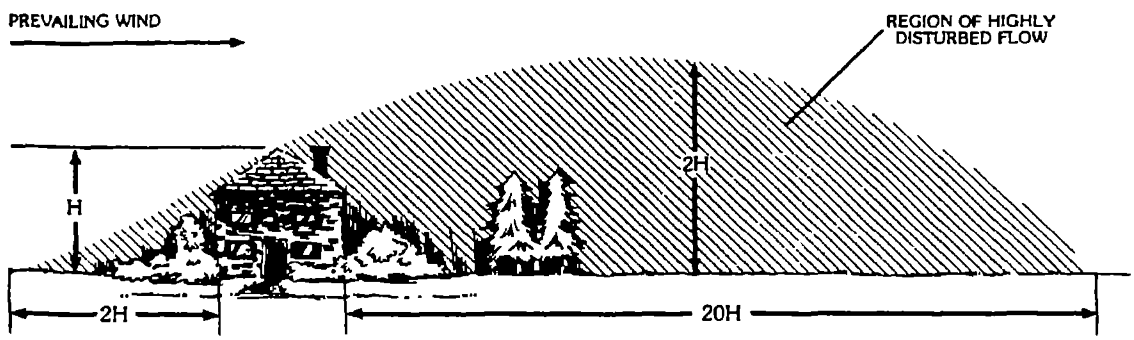
A correction for local terrain must be used to modify predicted windspeeds if surface conditions at the reference and pumping sites are significantly different. For all practical purposes, terrain characteristics can be divided into three groups:

- smooth—empty cropland and exposed airport locations,
- moderately rough—areas with small bushes or crops, and
- rough—woodland or areas with buildings.

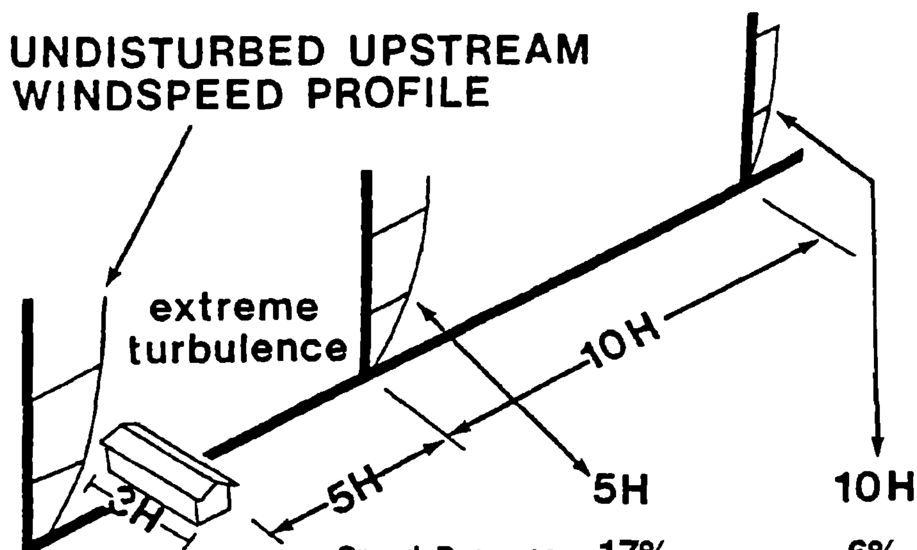
Suppose you have measured windspeed data from an anemometer installed at an airport two kilometers from the planned windmill site. In adjusting estimated windspeed between any two of these terrain categories, a 25 percent correction factor should be applied, decreasing the windspeed as surface roughness increases. Thus, if the planned site is open brushland, reduce windspeed estimates by 25 percent. If the site is wooded, reduce estimated windspeed by 50 percent. Figure 18 shows the effects of various obstacles on windspeed, along with the estimated reduction in power at different points behind the obstruction. For example, if a building has a height of H, at a distance of 5H downwind from the building the turbulence caused by the building reduces power by 43 percent. At a distance 10H downwind, the reduction in power is only 17 percent.

If the data recording period is short, there is a chance that average windspeeds based on the data may not truly represent long-term averages. If only one year of information is available, average speeds may be in error by 10 percent. Averages for longer periods (three years or more) are likely to be no more than 3 percent in error. If the duration of recorded data is only one year, it is suggested that average windspeeds be discounted by 10 percent as a safety factor to ensure that the windmill will not be undersized.

Figure 18



18a. Airflow disturbance around buildings and shelterbelt.



	5H	10H
Speed Decrease =	17%	6%
Turbulence Increase =	20%	5%
Wind Power Decrease =	43%	17%

18b. The effects of an undisturbed airflow encountering an obstruction.

Reference: V. Nelson and E. Gilmore, *Introduction to Wind Energy.* Alternative Energy Institute, Sept. 1984, Canyon, Texas.

If long-term data are available from a nearby meteorological station and you have recorded windspeeds for several months or more at your site (preferably during the expected design month--see below), there is a another simple but useful technique for extrapolating from meteorological data to a specific site. Divide the monthly average windspeeds at the site by the long-term averages for the same months measured at the meteorological site to obtain a correlation factor. Then, use this factor with the meteorological data to estimate the average monthly windspeeds at the site for months with no site-specific data (see Example 13).

Example 13: Windspeed Extrapolation from Another Site's Data

You have installed an anemometer at your site to measure windspeeds for several months. You recorded an average monthly windspeed of 5.0 m/sec in April. A nearby meteorological station (with an anemometer at the same height and similar terrain) measured 4.0 m/sec for the same month. Estimate the windspeed at your site for March, in which the meteorological station measured 3.5 m/sec.

The correlation factor is 5.0/4.0, or 1.25. You can then estimate that the average windspeed at your site in March was about 3.5 x 1.25, or 4.4 m/sec. The accuracy of this sort of extrapolation depends on how closely seasonal variations in wind at the site follow those at the weather station, but it generally gives a good estimate.

7.3.2 The Design Month

During the course of a normal year, there are periods of high and low winds. Over a number of years, the pattern of these periods will usually be fairly predictable and should be apparent from an examination of average monthly windspeeds for the region. The design month is the month when the ratio of the available wind energy divided by the average monthly water demand is the **lowest**. This means that in the design month the windmill will have the greatest difficulty in meeting demand. The system must be designed for this "worst case" condition.

In addition to average windspeeds, the water-demand profile at the site must be determined (see Chapter 2), so the design month can be determined. If the demand is constant throughout the year, the design month will be simply the month with the lowest average windspeed. If demand fluctuates from month to month, the design month is determined by dividing the average daily demand in cubic meters per day for each month by the average windspeed for that month, and then selecting the month with the highest ratio as the design month. This will be the month in which the water demand is the highest, compared to the available wind to meet that demand. Example 14 below shows how this is done.

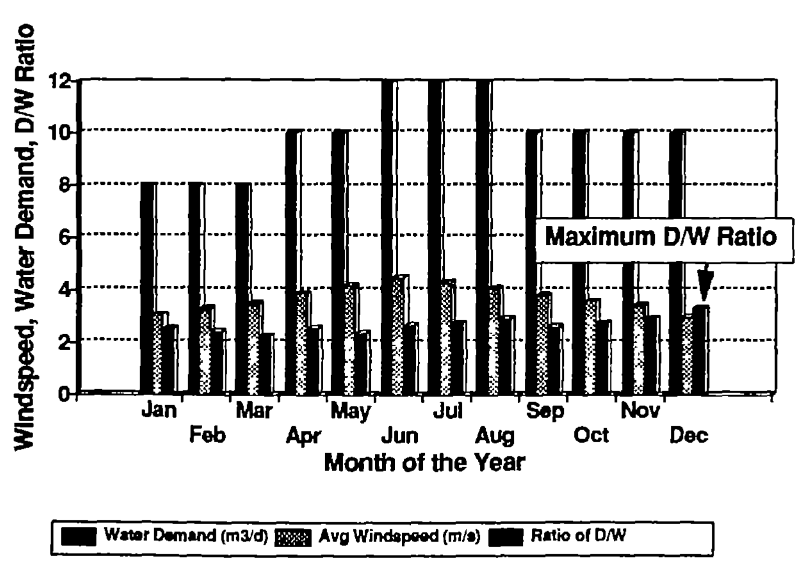
Example 14: Finding the Design Month

If monthly average windspeeds (in m/sec) and water demand (in cubic meters per day) are as shown in the table below, what is the design month windspeed for these conditions?

Month	Windspeed (m/sec)	Demand (m^3/day)	Ratio (D/W)
Jan	3.1	8	2.58
Feb	3.3	8	2.42
Mar	3.5	8	2.29
Apr	3.9	10	2.56
May	4.2	10	2.38
Jun	4.5	12	2.67
Jul	4.3	12	2.79
Aug	4.1	12	2.93
Sep	3.8	10	2.63
Oct	3.6	10	2.78
Nov	3.4	10	2.94
Dec	3.0	10	3.33

The month with the highest ratio of water demand to monthly windspeed is December (3.33), as shown on the accompanying graph.Therefore the design month windspeed to use for designing the system is 3.0 m/sec.

Figure 19.
Determining the Design Month
(Variable Water Demand and Windspeeds)



7.3.3 Required Rotor Diameter

The rotor size needed for a specific site depends on the pumping head, design windspeed, water demand, and overall system efficiency. Windmill output also depends on the pump cylinder chosen. A method for choosing the proper cylinder size is given in Section 7.3.4. At this stage, it will be assumed that an appropriate cylinder size is available. The calculation for selecting an appropriate rotor diameter is:

$$D_r^2 = \frac{(Q_D \times H)}{(\rho \times 7.9 \times V_d^3 \times \eta)}$$ **Formula #12**

where
- D_r = required windmill rotor diameter in meters
- Q_D = water required in m^3/day
- H = total pumping head in meters
- ρ = local air density in kg/m^3
- V_d = average windspeed for design month in m/sec
- η = assumed overall system efficiency (between 4-8%--see below)
- 7.9 = units conversion factor to get rotor diameter in meters

System efficiency depends in part on average windspeed. For conventional windmills, assume an efficiency of 4 percent for windspeeds between 2-3.5 m/sec. For 3.5-4.5 m/sec, use 6 percent efficiency. Above 4.5 m/sec, efficiency drops to around 5 percent. This is because windmills are designed to operate most efficiently at 4 m/sec. For improved windmills, such as the Kenyan Kijito, an efficiency of 8 percent should be used if windspeeds are 3.5 m/sec or higher, but this figure should be progressively reduced to 4 percent as the average windspeed declines to 2 m/sec.

Air density is closely related to air pressure and temperature. In most cases, altitude (i.e., pressure) is the largest factor in air-density calculations. Table 4 below gives correction factors for altitude (K_A) and temperature (K_T). To estimate air density for any altitude and temperature, multiply the density of standard air (1.22 kg/m^3 at sea level and 20° Centigrade) by both factors shown in Table 5. You could also consult local weather services to get a representative air density for your proposed site.

Table 5.
Air Density Correction Factors*

Altitude (m)	0	750	1,500	2,250	3,000
K_A	1	0.91	0.84	0.76	0.69

Temperature (°C)	-20	-10	0	10	20	30	40
K_T	1.27	1.13	1.07	1.02	0.99	0.96	0.93

Adapted from: J. Leki et al., *More Other Homes and Garbage* (Sierra Club Books, San Francisco, 1981).

Example 15: Estimating Air Density

Estimate the air density at 1,500 meters above sea level at 40° Centigrade. Under these conditions, $K_A = 0.835$ and $K_T = 0.925$. Therefore,

air density = 1.22 kg/m^3 x 0.835 x 0.925 = 0.94 kg/m^3.

(This means that for a climate like that in Botswana, the power available in the wind is only 77 percent of that at sea level and 10° Centigrade).

Example 16: Rotor Diameter

What is the required rotor diameter for a standard farm windmill if conditions during the design month are V_d = 3.6 m/s, H = 35 meters, Q_D = 7 m^3/day, with an air density of 1.0 kg/m^3?

$D_r^2 = (Q_D \times H)/(\rho \times 7.9 \times V_d^3 \times \eta)$

$D_r^2 = (7 \times 35)/1 \times 7.9 \times 3.6^3 \times 0.06)$

$D_r^2 = 11.1 \text{ m}^2$

Thus, D = 3.3 meters or 10.9 feet. To ensure you meet the demand, choose a windmill with a 12-foot diameter, the next largest commonly available size.

7.3.4 Sizing the Pump Cylinder

To size a pump cylinder properly for a windmill, you should understand the concept of system design ratio (X_d). This is the ratio of the system's design windspeed (v_d) to the average windspeed at the site for the design month, and is used to calculate the correctly sized cylinder. The system's design windspeed is the instantaneous operating windspeed at which system efficiency reaches a maximum. For steel-bladed, farm-type windmills, the design windspeed can be approximated as:

$$v_d^2 = .15 \times \frac{(S \times H \times D_c^2}{(D_r^3 \times G))}$$

Formula #13

where v_d = design windspeed in m/sec

.15 = units conversion

S = stroke length in centimeters

H = total head in meters

D_c = diameter of the pump cylinder in inches[1]

D_r = rotor diameter in meters

G = windmill gear ratio

[1] Cylinder size is almost always given in inches rather than millimeters.

Note that D_r and G are machine parameters that will depend on the windmill selected, and H varies with the site. A pump cylinder must be chosen based on the limited number of sizes available.

A windpump that is well matched to a site should reach its optimum efficiency around the average windspeed there. This is the case when X_d is 1.0, which means that your particular windmill's design windspeed is the same as the average windspeed for your site during the design month. In many instances, this is indeed true. However, for values of X_d slightly below 1.0, the windmill will operate for slightly longer periods (because it runs in lighter winds), but it will deliver less water overall, affecting the size of storage tank required. For values of X_d above 1.0, a windmill may deliver slightly more water on the average, but less during lower wind periods. In other words, using a lower X_D value (0.7-0.9 is recommended) will help ensure that you will have greater water availability during low windspeed periods. This means that users will have access to water a greater percentage of the time.

Your choice of X_D will depend to some extent on the elasticity of demand at the site, but a reasonable compromise is to **use a value for X_d of 0.8**. The proper cylinder size can then be determined using the following formula:

$$D_c^2 = \frac{((X_d \times v_d)^2 \times D_r^3 \times G)}{(.15 \times S \times H)}$$

Formula #14

where X_d = system design ratio

and all other variables are as defined in Formula #13 above.

Example 17: Cylinder Size

A Dempster windmill is to be installed at the site in Example 15. If X_d is 0.8, what is the proper cylinder size? Note that complete machine specifications should be given in the manufacturer's literature on the windmill. For a 12-foot (3.65 m) Dempster, they are a stroke length of 18.4 centimeters, a design windspeed of 3.6 m/sec, and gear ratio of 3:1. From Formula #14,

$D_c^2 = ((X_d \times v_d)^2 \times D_r^3 \times G)/(.15 \times S \times H)$

$D_c^2 = ((0.8 \times 3.6)^2 \times (3.65)^3 \times 3.0)/(.15 \times 18.4 \times 35)$

$D_c^2 = 12.5$

$D_c = 3.53$ inches

The sizing method given here is adequate for choosing a windmill and pump cylinder. However, it is possible to make more accurate estimations if more reliable and detailed information on the wind resource is available. Computer programs have been developed that permit more accurate and detailed estimates of windpump output. Contact the authors of this manual if you are interested in using such programs.

7.4 Cost Considerations

This section gives representative costs for several types of windmills and associated equipment, as well as typical recurrent O&M spare parts costs and requirements. For models from the same manufacturer, the capital cost of a windmill increases with increasing rotor diameter. As a general estimate, windmills cost between US$200 and US$500 (not including towers) per square meter of rotor area, depending largely on the country of manufacture. Tower costs are proportional to height. For the same-size rotor, traditional designs (e.g., Southern Cross and Fiasa) are sometimes less expensive than "improved" models (Kijito or CWD-5000), but the price is highly dependent on the country of origin. For example, a 16-foot Fiasa on a 40-foot tower costs about US$13,600, shipped from Fiasa Windmills in the United States, and a 12-foot model on the same tower costs US$6,500. In contrast, a Kijito from Kenya costs about US$11,000 for a 24-foot diameter rotor on a 40-foot tower, shipped from Mombasa, while a 12-foot Kijito costs US$5,000.

The price of a pump cylinder depends on the manufacturer, the diameter, and the material. Cylinders manufactured in developing countries are generally less expensive and can be of good quality depending on their source. They are typically available in the 2- to 4-inch diameter range for US$200 to US$800, with larger sizes costing more. The cost of even larger cylinders increases greatly. Most cylinders are made of brass. Stainless-steel cylinders can be purchased for sites with very corrosive water, but they are often prohibitively expensive ($1,500 or more).

The prices given here for windmills and cylinders are current as of 1989, but may vary with new design and manufacturing developments. They also depend on the country of origin—for instance, Kijitos are made in both Kenya and Pakistan but are sold for different prices. The prices quoted here do not include shipping and insurance or local import tariffs and restrictions. If possible, contact a local distributor to get more accurate prices for your area.

7.5 Maintenance and Repair

As is true of all pumping equipment, the quality of windmill operation and preventive and corrective maintenance (defined in Section 5.5) will have a definite impact on the reliability of the system, the magnitude of recurrent costs, and the life of the equipment.

Most wind systems do not need a full-time operator, unlike diesel pump sets. When the wind blows, the windmill pumps water. All farm windmills and most of the improved designs have safety mechanisms to turn the rotor out of the wind to protect it during periods of high wind. Despite these self-regulating design features, a part-time operator or caretaker is advisable for a number of reasons. His or her tasks would include the following:

- periodically checking the windmill and storage tank;
- performing light maintenance;
- manually furling the windmill when the storage tank is full and unfurling it when more water can be added; and
- reporting any major repair needs to repair crews.

The issue of paying a part-time operator or caretaker will vary depending on the pump application and community structure. It should be noted that the cost of this item can make a difference in determining the economic and financial feasibility of a windpump.

While normal preventive maintenance requirements for windmills are minimal, they are important. They include routine tightening of all nuts and bolts, changing the lubricating oil, greasing certain parts, and periodically changing the pump-cylinder leathers as they wear out. Ignoring any of these small tasks can damage the machine and, at best, will decrease its expected service life. If these tasks can be accomplished by a local caretaker instead of a circuit rider mechanic (one who is responsible for a number of windmills throughout the area), operating costs will be reduced because labor and transportation costs will be saved. In addition, the system is likely to be more reliable if responsibility for maintenance rests with someone who benefits directly from its proper operation. This is not possible with some more difficult tasks, however, such as changing pump-cylinder leathers, which usually requires tools for pipe lifting.

The frequency of routine maintenance depends on conditions at the site. It is recommended that windmills be checked visually at least once a month and remaining maintenance tasks be carried out annually. The life of cylinder cup leathers depends to some degree on water quality (i.e., grit or sand in the water) and may range from six months to over two years. In the absence of other information, an average replacement interval of one year is a reasonable estimate for planning purposes.

The most common minor maintenance problems typically involve the windmill's manual furling mechanism. Broken furling cables do not disable the windmill and, in most cases, the problem can be rectified at the local level. However, if left unrepaired, a broken furling mechanism will prevent the windmill from being manually turned out of high winds, which could cause irreparable damage.

Outside assistance is usually needed to restore the windmill to operation after a breakdown. The most common causes of breakdowns are broken or disconnected pump rods. How often this problem arises is highly dependent on the quality of the original installation. Improperly installed rods or crooked borehole casings can cause regular breakage of sucker rods. The problem may arise only every several years or as often as every few months. A typical rate for a reasonably well installed system is once a year.

Field experience in several African countries indicates that an average windmill installation will have three to four maintenance problems annually. The reliability and serviceable life of the windmill will be increased and costs decreased in proportion to the amount of maintenance and repair work that can be handled at the local level, as well as the responsiveness and capability of outside technical help when it is required.

7.6 Equipment Life

The long-term cost-effectiveness of windmills depends on a system having low recurrent costs and a long useful life. Historically, the popularity of steel-bladed, farm-type windmills in many areas was due to these attributes, with typical lifetimes often in excess of 20 years and occasionally as long as 40 to 50. Windmills have not had such a favorable record in developing countries. Often, the first or second breakdown has been the end of a windmill's useful life, because local people were not often trained in proper operation and repair procedures when the system was installed. This emphasizes the importance of identifying a capable maintenance and repair organization before installing a windpump, and establishing a satisfactory, cooperative, and responsive relationship between that organization and the users of the system to ensure a long, useful life for the windmill.

Chapter 8: Handpumps

Considerable research and development have been undertaken over the last 10 years in an effort to produce more efficient, reliable, low cost handpumps that can be manufactured locally. As part of the United Nation's International Drinking Water Supply and Sanitation Decade, the World Bank has funded comparative studies of handpumps that have focused on the concept of village-level operation and management of maintenance (VLOM). VLOM pumps can easily be installed, operated, and maintained by village mechanics and technicians without expensive tools.

It is increasingly apparent that handpumps are the least expensive, most reliable technology for many applications, particularly for low-demand sites (about 5 m^3/day). However, anyone who works in the water supply sector in developing countries has seen many inoperative handpumps. Nonetheless, when properly maintained, handpumps can be very reliable, although community involvement in maintenance and repair is usually required to ensure successful long-term performance. This involvement minimizes the need for O&M support from outside the local community, making handpumps a more attractive option to development planners and, more importantly, users. Handpumps that can be maintained locally are likely to result in much higher water availability for the community, compared to other systems where maintenance or repair depend on the intervention of regionally-based repair crews which are often overburdened.

This chapter discusses the technical characteristics, costs, and support requirements of handpumps for domestic water supply. Sizing is a much less complex design issue for handpumps than for the other systems discussed in this manual, so the selection criteria presented here focus more on other issues related to maintenance and repair. There is a wide variety of human-powered pumping systems that are used primarily for agricultural purposes, including foot-powered treadles, shadoofs, and chain-and-washer pumps, but these will not be discussed further here. Kennedy and Rogers (1985) and Fraenkel (1986) offer in-depth discussions of these other types of human-powered pumps. This chapter draws heavily on the excellent reference *Community Water Supply--the Handpump Option*[1], and you are encouraged to get a copy for reference, especially if you are planning any significant project use of handpumps.

8.1 Types of Handpumps

Over 50 makes and models of handpumps are available worldwide. All depend on human power and, thus, have a limited pumping rate and head range compared to the other mechanical systems considered in this manual. Handpumps can be divided into four categories:

- suction pumps—up to 7 meters;
- low lift—up to 12 meters;
- intermediate lift—up to 25 meters; and

[1] S. Arlosoroff et al., World Bank, Rural Water Supply Handpump Project, Washington, DC, 1987.

- high lift—positive-displacement pumps capable of pumping from depths of up to about 50 meters or more.

These categories include high-lift reciprocating, diaphragm, progressive-cavity, direct-action, and suction pumps. Illustrations of several common types of pumps are shown in Figure 20. Two typical installations are shown in Photographs 10 and 11.

Deep-well reciprocating-piston pumps are the best-known type of high-lift pumps. They usually have submerged pump cylinders, and are operated with lever-arm pump handles. Common designs are the India Mark II and Afridev. These pumps can lift water from about 50 meters, although some other designs are more suitable for lifts of less than 25 meters. Typically, high-lift piston pumps are:

- more difficult and expensive to maintain at the village level than low-lift pumps;
- operated at a decreased pumping rate as head increases; and
- generally less suitable for local manufacture in developing countries.

A second design suitable for high-lift pumping is the progressive-cavity pump. Similar to a screw pump in its operation, this design incorporates a rotor turning within a stator that progressively forces water up the drop pipe. The Mono and Moyno brands are examples of this design.

A third type of high-lift pump is the deep-well diaphragm design. It uses a flexible membrane that is repeatedly stretched and relaxed mechanically to provide the pumping action. The French Vergnet is perhaps the best example of this type. These pumps are especially suitable for sandy or silty water. However, compared to reciprocating-piston pumps, they are generally more complex and expensive, and often require specialized parts and tools for maintenance and repair.

Direct-action pumps, such as the Blair and Kangaroo pumps, are suitable only for lifts up to about 12 meters because the pumper acts directly on the pump, without the advantage of a lever arm. Compared to the designs mentioned above, these pumps tend to be:

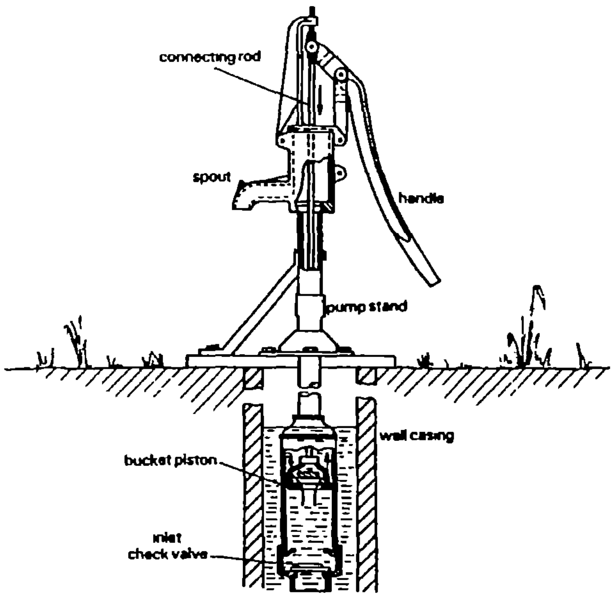
- low in cost;
- more suitable for village-level maintenance; and
- inappropriate for heavy use—they should probably not be considered for sites where the water demand is above 1.5 to 2 m^3/day.

Suction pumps operate by creating a partial vacuum to pull water upward. Thus, they are useful only for lifts of no more than 7 meters (a limit that decreases at higher altitudes). Suction pumps must also be primed before use by pouring water into the space above the plunger. Still, these pumps are very popular in areas where heads are low. This type of pump tends to be:

- low in cost;
- easy to service and repair because all moving components are at ground level; and
- primarily suited to meeting fairly limited water needs.

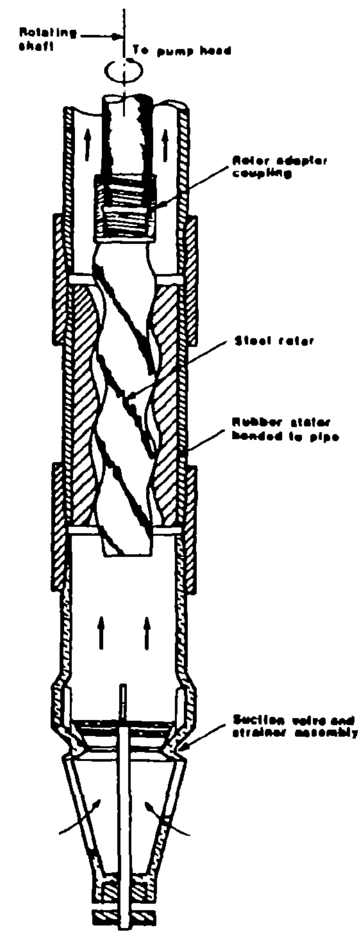
S. :e low- and intermediate-lift pumps are essentially simplified versions of high-lift pumps, only high-lift and suction pumps will be discussed further in this chapter.

Figure 20. Different Types of Handpumps

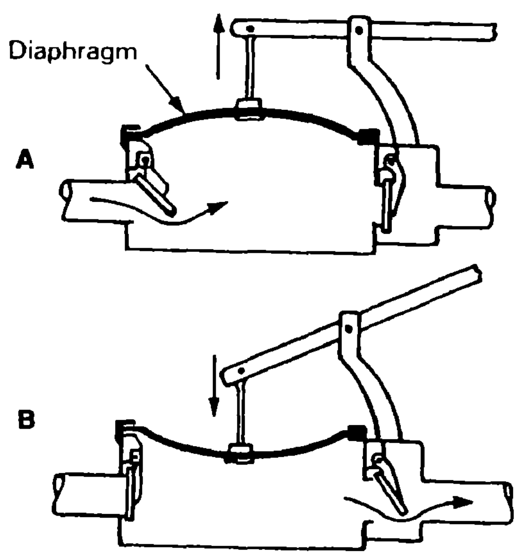


Deep Well Piston Pump**

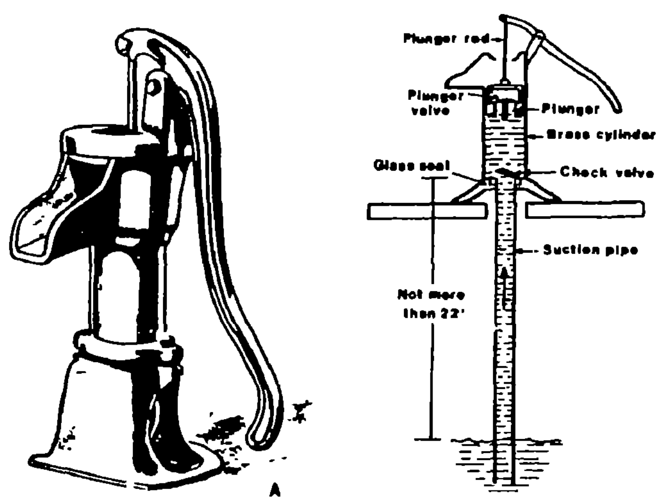
Direct Action Power Pump**



Helical Rotary (Mono) Pump*



Surface Mounted Diaphragm Pump*



Shallow Well Suction Pump*

*(McJunken 1983)
**(Fraenkel 1986)

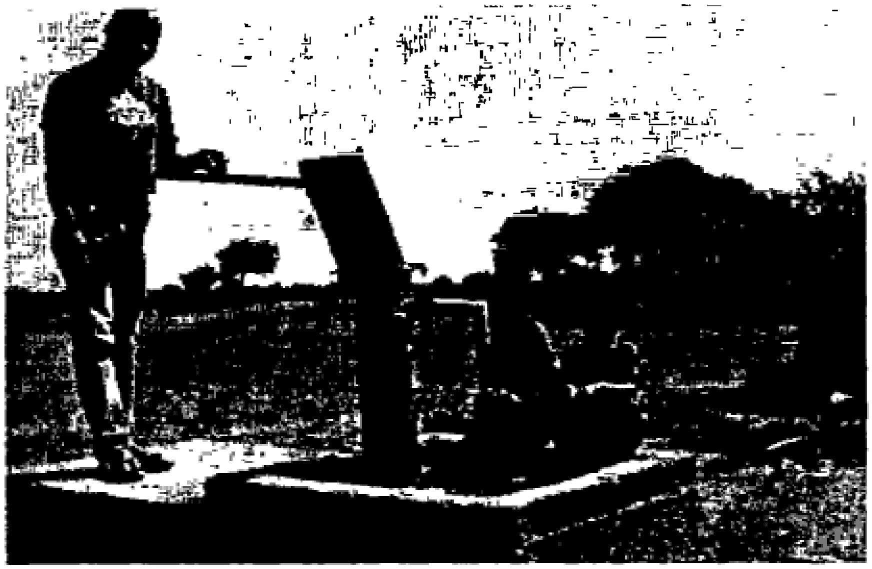


Photo 10.

India Mark II Piston Handpump in Botswana

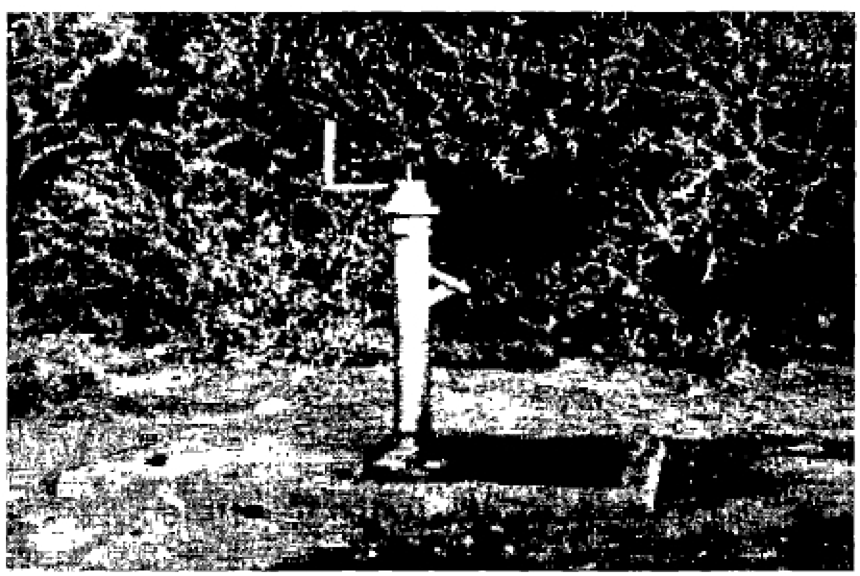


Photo 11.

Mono Direct Drive Handpump in Botswana

8.2 Operating Characteristics

The operating characteristics and requirements of handpumps are significantly different from those of diesel, solar, and wind systems, and include both advantages and disadvantages. The most important advantages of handpumps are their simplicity of operation, low cost, and potential for local maintenance. The significant disadvantages of handpumps are that their capacity is very limited and they generally cannot be used with piped distribution systems. To some extent, these drawbacks can be overcome by using more than one pump. Of course, this would usually require additional water sources[2], which would entail high costs for drilling or digging more wells at sites where groundwater is pumped.

The capacity of handpumps varies from about 5 to 20 liters per minute, or 0.3 to 1.2 m^3 per hour on a continuous basis, depending on the pumping head and pump type. In practice, output is often more dependent on the users' strength, stamina, and group behavior than on the capacity of the pump. Even if people are organized, lined up, and ready to begin pumping as soon as the preceding person finishes, it still takes time to remove the full container under the discharge pipe and replace it with an empty container. Output is also affected by the speed (i.e., effort) with which a pump is used, a factor that varies considerably from user to user. Under typical conditions (for instance, at 45 m head), a single handpump can deliver 4 to 5 m^3/day, enough for 200 to 250 people. At 20 m head, you would get about 8-10 m^3/day. This capacity limits the use of handpumps to villages and settlements with small populations, even if multiple pumps are installed. Depending on particular site constraints, a system of four or five handpumps may provide a reliable water supply that is cost-competitive with other options. This, of course, depends on the costs of digging the wells for each pump.

Usually handpumps deliver water only to the wellhead, and cannot easily be adapted to central-standpipe or yard-tap distribution systems. This fact has two implications. First, water sources should be within a convenient walking distance for users. Any economic analysis of the number of water points to be included in a system should consider the opportunity cost of time required to collect water. Second, compared to distributed water supplies, significant capital savings are realized because a storage and distribution system is not needed.

8.3 Maintenance and Repair

Maintenance programs for pumping systems are usually handled by the community or a regionally-based maintenance and repair organization. In the former case (e.g., VLOM), the community takes direct responsibility for the pumping system and only contacts outside help for repairs if necessary. In regionally-based programs, responsibility for a system rests with an outside agency contacted by the community whenever any servicing is required that they cannot do themselves. Studies over the last several years have repeatedly shown that community involvement is an important factor in successful long-term operation of handpumps. To the greatest extent possible, community participation in pumping projects should be encouraged from the earliest planning stages.

[2] Although in some areas, like Sudan, two handpumps are installed on the same large diameter (1-2 meter) open well.

As is true for more complex technologies, the proper design, procurement, and installation of handpumps are necessary, though not sufficient, conditions for successful long-term use. Correct operation, maintenance, and repair procedures are equally important. The VLOM approach to handpump design focuses on reducing users' dependence on external support. This approach can save money and time and can also minimize other problems (e.g., communication, transportation, and improper repairs) often associated with regionally supported maintenance and repair programs. Since handpumps are relatively simple pumping systems, they are well suited to the VLOM approach.

VLOM programs provide an O&M structure that is more directly responsive to community needs than regionally based programs. However, centralized programs with mobile mechanics that serve specific geographic areas can complement the VLOM model by mobilizing trained mechanics, tools, and transportation when more complicated repairs are required. VLOM programs usually include training to identify and then develop the capability of a village caretaker to perform light maintenance, prevent abuse of the pump through improper operation or vandalism, and quickly summon outside help for maintenance and repairs as required. Caretaker effectiveness is the critical component in successful handpump use.

Regular preventive maintenance for handpumps—for instance, tightening nuts and bolts, checking for cracks in the well apron, cleaning drainage lines, and keeping the area clean—should be performed at the local level by the village caretaker. Most common handpumps are not truly VLOM designs, so it is often impossible to handle all maintenance and repair at the village level. Often, repairs are required when below-ground components fail due to poor water quality, heavy use, or simple wear. This type of work usually involves the transportation of a repair crew with appropriate tools from a central workshop. In such cases, a prompt response is necessary to ensure a steady supply of water.

For convenience, maintenance and repair needs have been divided into nine potential problem areas:

- the pump handle;
- the fulcrum or bearings (which will wear over time, especially if pumping from higher head);
- the rod hanger, where the sucker or pump rods attach to the bottom of the fulcrum;
- the pump rods (which can corrode or become disconnected from each other or the pump element;
- the rising main or drop pipe (which can clog or corrode);
- the piston seal, often referred to as the leathers (which wear under normal conditions and need periodic replacement)
- the pumping element—for example, the piston in reciprocating pumps and the diaphragm in diaphragm pumps;
- the foot valve, which prevents water from draining out of the drop pipe and causing a loss of priming in suction pumps); and
- other problems.

For piston pumps (including high-lift reciprocating, low-lift suction, and direct-action types), the leathers are typically the most common item needing repair. They will probably require replacement every six months to two years, depending on the quality of the water and the degree of pump use, with heavy use increasing the frequency of replacement. The cylinders probably will last five to seven years, depending on the same factors. A typical maintenance and repair crew can replace the leathers or cylinders in one day (not including transportation to the site), even if the cylinder and drop pipes have to be pulled. If the drop pipes have to be pulled, a special rig or tripod may be needed to lift them from the borehole, depending on their length and weight.

The bearings on the pump handle are the second most common problem area in piston pumps. Depending on the design, the replacement of bearings can be very difficult. New pump designs, such as the Afridev, use plastic bearings that can be easily replaced in order to minimize this problem.

For Mono-type pumps, the bobbins holding the pump rods in place will have to be replaced periodically, in addition to the pump rods and drop pipes. In general, the pump itself is very long-lasting and will probably require replacement only every seven to ten years under normal use. For diaphragm pumps, the part that is most likely to need periodic replacement is the diaphragm, every three to five years. Typical frequencies for the maintenance and repair needs of many pumps are given in the "Handpump Compendium" section in Arlosoroff et al. 1987.

A typical range for frequency of repairs needed for community handpumps is between three times a year and once every two years. The level that is acceptable will depend on the responsiveness of the repair infrastructure and the total amount of time the pump is out of service. If repairs can be done at the local level, outages will be shorter and a higher breakdown frequency may be acceptable to users. If repairs must be done by a centralized maintenance unit, it may take several days or more before problems are addressed, and a greater frequency of repairs is not so likely to be tolerated.

The expected lifetime for handpumps is difficult to estimate as it depends on the conditions and amount of use as well as care the equipment has received. However, typical ranges are anywhere from 5 to 10 years. For example, at one CARE-assisted community on Sumbawa Island in Indonesia, the majority of the locally manufactured handpumps installed nearly ten years ago (and maintained by villagers) are still operating.

8.4 Choosing a Handpump System and Model

People are often reluctant to consider handpumps because of their obvious capacity limitations, despite the equally obvious potential for cost savings. The following sections offer some basic recommendations on handpump use to help you determine whether or not handpumps are the right choice for your site.

8.4.1 Application Limits

Handpumps should not be considered if the total head at your site is more than about 50 meters, due to the physical difficulty of pumping water from greater depths. You should also take into account whether the maximum anticipated head will be further increased by excessive drawdown in very low-yield wells or seasonal fluctuations of the water source—both are likely with shallower sources that are more dependent on seasonal recharge.

While some deepwell hand pumps can be used for depths up to 80 meters, it is generally not advisable to do so. For example, if counterweights are added on the end of the lever of an India Mark II, or if an intermediate cylinder is used at a depth of 30 meters, a Mark II can be used at total heads of 70-80 meters. However, this increases the number of parts, puts much greater stress on downhole piping, pump rods, and pump bushings, and therefore increases maintenance costs and decreases pump reliability. Therefore, handpumps should in general not be used for total heads of greater than 50 meters, both for reliability reasons and due to the increased difficulty of pumping water from those depths.

If the maximum anticipated pumping head is less than 50 meters, the next concern is the water requirement. Given that a typical handpump can serve 200 to 250 people (i.e., provide 4 to 5 m^3/day), the number of handpumps and wells needed for larger sites can easily be calculated. In some circumstances (e.g., very remote sites where diesel fuel may be expensive or difficult to obtain and where qualified technicians may not be available), four to five handpumps may be a more attractive option than a single diesel pump with greater pumping capacity and the associated water storage and distribution system (see Photo 12). The cost of developing additional wells, water storage and distribution systems, and the maintenance associated with these components must be considered in deciding which type of system to use (see Chapter 10 for an economic analysis of pumping systems).

Convenience and health concerns should be considered in system design and siting. Convenient well siting is not as important for pumping systems that can distribute water through central standpipes or private connections. However, for handpumps to be a viable option, they should be located no more

Photo 12.

Women using one of several handpumps installed on shallow tubewells in a refugee camp south of Khartoum, Sudan.

than a reasonable walking distance from users--400 to 500 meters if at all possible. At sites where water sources are located well outside village boundaries (perhaps to reduce the risk of pollution), handpumps are probably not suitable because of the distance and thus the time that would be required to collect water. The need to prevent well pollution is also important. Pollution may occur through direct entry, as occurs with open, hand-dug wells, or the migration of contaminants from the surface. Provisions should be made for a well apron and "soak-away" or drain to keep the area around the well as clean and dry as possible.[3]

8.4.2 Selecting a Handpump Model

In terms of equipment, the design process for handpumps consists mainly of choosing the pump and, in a few cases, an appropriate cylinder. Many handpumps come already equipped with a fixed-sized cylinder. Pump selection depends on anticipated maximum lift, water demands, discharge rate, ease of maintenance and reliability, and resistance to corrosion and abrasion. Additional concerns are the local availability of the pump and, where appropriate, the potential for local manufacture. When selecting a pump, consider these factors in the following order:

- operating conditions—head and water demand;
- ease of maintenance—which is dependent on the local O&M infrastructure;
- reliability—see the ratings discussed below;
- resistance to corrosive or abrasive water conditions; and
- potential for local manufacture of the entire pump or some of its components.

If you determine that handpumps are the most appropriate technology, based on the water demand at the site and other factors given above, the best single source of information on choosing a particular pump manufacturer and model is Arlosoroff et al. 1987 (Chapters 5 and 6). The section titled "Handpump Compendium" contains summary descriptions of over 100 makes, 86 of which were tested during the World Bank's handpump project. Each description includes an overall assessment and ratings on discharge rate, ease of maintenance, reliability, corrosion resistance, abrasion resistance, and manufacturing needs. After first determining which pumps can be procured locally, use this reference to choose between the available models. The book also contains a set of four pump selection tables organized according to head limits: 7, 12, 25, and 45 meters. Within these four categories, pumps are rated on each of the six areas listed above. These summary selection tables are reproduced in Appendix D of this manual. An example of their use is given on page 111 below.

In many areas, handpumps can be purchased only through agents from abroad. In others, imported handpumps can be ordered through a local dealer or distributor. Occasionally, local suppliers stock imported pumps or even models manufactured locally. There is increasing interest in promoting the local fabrication of handpumps in countries where the industrial capacity is sufficient to ensure high-quality products. The advantages of in-country manufacturing include:

- cost savings resulting from lower labor and shipping costs;

[3] See *Rehabilitation of Rural Water Systems* by the authors of this manual for a more detailed discussion. WASH Technical Report Series, the WASH Project, 1992.

- local technicians' familiarity with the units, thereby ensuring better maintenance and repair capabilities;
- increased availability of spare parts; and
- local income generation.

In addition to a moderately developed industrial capability, a suitable local or regional market must exist before local manufacturing of handpumps should be considered. At the project level, the decision to use handpumps should include an evaluation of the potential for future fabrication of the entire pump or some components. If local manufacturing is seriously considered, various associated needs must be studied. High-quality manufacturing of pumps and/or spare parts can be an expensive, time-consuming project. The implications and cost of such a program must be considered carefully within the overall context of a country-wide water resources development strategy.

8.5 Cost Considerations

When comparing water costs using handpumps with those for other technologies considered in this manual, special care must be taken to include all relevant costs. Only those items that are common to all systems can be ignored in such comparisons. For example, if you consider using multiple handpumps to meet a demand for distributed water, you must include the cost of developing multiple water sources. Similarly, if this is to be weighed against the cost of a distributed water supply provided by a diesel pump, remember to include costs for piped distribution, water storage, and associated maintenance and upkeep. If water users are going to be expected to pay (in part or in full) for the additional cost of the convenience of distributed water, make sure that they are willing and able to do so. This can represent a substantial increase in the basic system cost.

The installed capital cost of a handpump varies depending on the type of system and its location. Prices given here are for 1992. Low-head pumps typically cost US$200, but may be as low as US$100, particularly when they are manufactured locally. Pumps for higher heads, which are usually imported, can cost considerably more, between US$300 and US$1,000 per unit plus shipping. Pump or sucker rods cost about US$2 to US$3 per meter[4] and drop pipe about US$5 to US$7 per meter. When installing a handpump on an existing open well, the cost for a well cap and concrete drain varies considerably depending on local labor and cement costs, but averages around US$50 to US$100.

8.5.1 Operating Costs

Handpump operation is fairly straightforward. The only "fuel" cost is the pumper's salary, if any. Most often, people pump their own water at no charge. Even so, a proper economic analysis of handpumps should consider the labor cost of pumping water. When considering different system options, be sure to include **all the costs** of supplying water. For example, some handpump sites may be located outside the village. If you are comparing a handpump system (where water users must carry water from the pump site to their village) to a diesel or other system which pumps water to public,

[4] Stainless steel rods, which should be used in corrosive water conditions, are much higher.

Selecting a Handpump Model

(see tables in Appendix D)

This example is typical of an alluvial plain in Asia, with a permeable aquifer and a high groundwater level. A maximum user group of 75 people per handpump is desired, with a demand of 20 liters per person per day (i.e. each pump must supply 1.5 cubic meters of water a day). Very little drawdown is expected during pumping, but nearby motorized pumps may lower the water table locally in some areas to 10 meters below the surface. The groundwater is not corrosive, and only trace amounts of sand may enter the wells during pumping. Village-level maintenance is to be introduced, as is in-country manufacture of handpumps, in a country with a medium level industrial base. Two pumps are already widely used in the country - The India Mark II (imported) and the New No 6 (locally made).

The first step in selecting a short list of pumps for this application is to complete Form 5.1 with the specific Selection Criteria. The figure below includes a copy of the form completed according to the criteria identified by the Analyst. Note that there is no Pump Selection Table precisely matching the operating condition of 10 meters maximum pumping lift, so the Analyst opts for Table S.2 (12 meters), ensuring that the most severe conditions are met.

HANDPUMP SELECTION CRITERIA

NAME OF PROJECT ______ Worked Example No.1

MAXIMUM PUMPING LIFT — 10 meters
Selection Table for this lift[1] — S.2

DAILY OUTPUT PER PUMP — 1.5 m^3/d

MAINTENANCE SYSTEM TO BE USED (A, B, or C) — A
Where A = Village-level maintenance
B = Area-mechanic maintenance
C = Centralized maintenance

MINIMUM RATING NEEDED FOR CORROSION RESISTANCE — —
Where — = Corrosion resistance is not required
o = Resistance to mildly corrosive water is required
oo = Resistance to aggressive water is required

MINIMUM RATING NEEDED FOR ABRASION RESISTANCE — —
Where — = Either there is no sand pumping anticipated, or there is a possibility of trace sand pumping and the daily output will not be greater than 1.5m^3
o = There is a possibility of trace sand pumping and the daily output will be greater than 1 5m^3
oo = There is a possibility of significant sand pumping

MANUFACTURING ENVIRONMENT (1, 2, or 3) — 2
Where 1 = The pump is to be made in the country, and there is a low-level industrial base
2 = The pump is to be made in the country, and there is a medium-level industrial base
3 = The pump may be imported or made in a country where there is a high level industrial base

PUMPS ALREADY PERFORMING SATISFACTORILY IN THE COUNTRY (* IF ALSO MANUFACTURED IN THE COUNTRY) — New No.6*, India Mark II

(continued next page)

Selecting a Handpump Model—continued

From the criteria listed on Form 5.1, the Analyst determines that for a pump to meet his minimum requirements it must achieve ratings in Table S.2 as follows:

Column No. in Table S.2	Criterion	Minimum rating
3	Discharge rate	o
4(A)	Ease of maintenance at village level	o
5 (1.5)	Reliability for output of $1.5m^3$/day	o
6	Corrosion resistance	—
7	Abrasion resistance	—
8 (2)	Manufacturing needs in medium-level industrial base	o

Each of the pumps in Table S.2 is evaluated, to check whether it achieves these minimum ratings Figure 6.2 shows the completed Table S.2, revealing that just 6 pumps met the minimum requirements (the desire for village-level maintenance and local manufacture eliminates many on the list). Neither of the pumps currently in use in the country make the Short List - the **New No. 6** is a suction pump and so cannot be considered for lifts of more than 7 meters, and the **India Mark II** is not appropriate for village-level maintenance. The six short-listed pumps therefore are: the **Afridev, Blair, IDRC-UM, Nira AF85, Tara and Volanta**.

This narrowing of the choice is a very important step in the selection process, as it produces a manageable list for detailed analysis in the final selection stage. In this particular example, further reduction of the short list will depend on the priority given to individual attributes, and on prices. For example, the **Blair** has a lower rating (**o**) than the others (**oo**) for discharge, the **IDRC-UM** and **Volanta** lower ratings for ease of maintenance, and the **Tara** a lower rating for reliability. Five of the pumps rank equally (**oo**) for local manufacture, which in this case is an important criterion. Consequently, potential manufactures in the country should be contacted to obtain assessments of their capacities for manufacturing the six pumps under consideration, and the prices for doing so with adequate quality control.

Adapted from:

Community Water Supply--the Handpump Option
S. Arlosoroff et al., World Bank, Rural Water Supply Handpump Project, Washington, DC, 1987.

centrally located standpipes, the cost of any additional labor for carrying water from the handpump site to the central location should be included in the analysis, although this labor cost is typically very small.

Handpumps require a time and labor commitment from users who could use that time in other ways if another pumping option were chosen. This is not usually a factor when considering diesel, solar, or wind pumps. As mentioned above, daily care of a handpump should be entrusted to a caretaker who has some skills and perhaps enough tools to permit him or her to fix minor problems. This person may or may not be paid by the community or as an employee of some public agency.

8.5.2 Maintenance and Repair Costs

The overall cost of installing, operating, and maintaining handpumps (or any other type of pump) depends very much on the specific circumstances of the individual site, what kind of equipment is used, and what level of service (public tap at the wellhead, public taps distributed throughout the community, or taps in individual yards) is provided. Because of the great need in rural, peri-urban, and even urban areas throughout the world for improved water supplies coupled with the limited financial support available for rural infrastructure development, more widespread use of inexpensive handpumps holds considerable promise for addressing this problem.

An example of the comparative costs for handpumps and piped distribution systems using motorized pumps is given in Table 5 below. You can see that for small communities (400 people using 8 m^3/day) using either the low- or high-cost assumptions (from a range of typical situations in developing countries), using handpumps (low estimate of $0.058 per capita) is roughly 2/3 the cost of motorized systems with public standpipes ($0.084), or 1/2 the cost of motorized systems with yard taps ($0.116).

Besides the obvious technical and cost issues associated with using handpumps for community water supplies, there is also the problem of social acceptance to confront. User groups may feel that handpumps are a technology of the past, and may not be willing accept the installation of a handpump (rather than, for instance, a diesel) if they think they have a choice. They may feel that the many failed handpump programs implemented in the recent past give further evidence of their inappropriateness. They may want what they perceive to be more modern technologies (usually diesel or electric pumps) which can meet their ever-increasing needs for ample, convenient water supplies.

The problem often comes down to affordability. If communities can afford to install and maintain these higher cost and more complex technologies themselves, they should be encouraged to do so, as long as they fully understand the associated financial and organizational support requirements. However, for donor or government-subsidized water supply programs, if handpumps are a technically feasible option, it is recommended that communities only receive higher levels of service if they are willing to pay for them themselves. To expect that government or donor agencies should both install and maintain these higher cost technologies is neither realistic nor possible in most developing countries.

Table 5. Community Water Supply Technology Costs (for a community of 400 people)[5]

	Low			High		
Technology	Handpumps	Standpipes	Yardtaps	Handpumps	Standpipes	Yardtaps
Capital Cost (US$)						
Wells[1]	4,000	2,000	2,500	10,000	5,000	6,000
Pumps (hand/motor)	1,300	4,000	4,500	2,500	8,000	9,000
Distribution[2]	none	4,500	16,000	none	10,000	30,000
Cost per capita	13.3	26.3	57.5	31.2	57.5	
Annual Cost (US$ per year)						
Annualized Capital[3]	700	1,500	3,200	1,400	3,000	6,000
Maintenance	200	600	1,000	400	1,200	2,000
Operation	none	150	450	none	300	900
Haul Costs (labor)[4]	1,400	1,100	none	3,000	2,200	none
Total Annualized Cost per capita						
Cash only	2.3	5.6	11.6	4.5	11.8	22.3
Cash plus Labor	5.8	8.4	11.6	12.0	17.3	22.3

[1] Pumping water level assumed to be 20 meters. Two wells assumed for handpump system (200 persons per handpump).
[2] Distribution system includes storage, piping, and taps with soakaway pits.
[3] Capital costs with replacement of mechanical equipment after 10 years annualized at a discount rate of 10% over 20 years.
[4] Labor costs for walking to the water point, queuing, filling the container, and carrying the water back to the house. Time valued at US$ 0.125/hour.

[5] Adapted from *Community Water Supplies, the Handpump Option*, the UNDP/World Bank Rural water Supply Handpumps Project, 1987.

Chapter 9: Operation, Maintenance, and Repair

Technical selection of pumping equipment has been explained in detail in the preceding chapters. By now, you should be able to determine which systems meet or fail to meet the pumping requirements at your site. If no systems can do so, a reevaluation of the criteria, site, or project is necessary. Assuming that you have narrowed the choice down to one or more system options that are technically acceptable, you must now determine whether these pumping systems can be operated and maintained properly.

To do this, you must weigh a number of additional factors related to the physical equipment, pump users, and infrastructural support network that keeps the equipment operating over the long run (system designers, equipment dealers, installation personnel, operators, and maintenance and repair crews). These factors are not nearly so easy to quantify as the head, the flow rate, and the various cost issues discussed in previous sections. As a decision-maker, you must determine what these factors are and weigh their relative importance.

To insure that proper operation, maintenance, and repair support will be adequate and available so the system will continue to supply water reliably over the long term requires an infrastructure that includes:

- spare parts and materials (including fuel) inventories;
- skilled operators and mechanics;
- transportation networks;
- communication; and
- organizational and financial management.

In the five categories of maintenance requirements covered below, questions are posed to determine whether the local or regional infrastructure will be able to support the specific type, make, and model of equipment you are considering.

9.1 Spare Parts and Materials

The most important factor determining whether a pumping system can be operated and maintained over the long run is the availability of spare parts, fuel (if required), and lubricants. All necessary parts and materials required for the system you select must be available nearby, otherwise the pump's first failure may mean the end of its service life. Servicing guidelines for diesel engines (often provided by manufacturers) usually divide spare parts into two groups—fast-moving spares and other parts. Fast-moving parts include items needed for preventive procedures and common corrective maintenance, such as gaskets, belts, and injector nozzles. These should be readily available for the engine make and model you choose. Other spare parts that are less commonly needed include cylinder heads, crankshafts, and flywheels. These must also be available, but since the need for them is likely to be less frequent, you may be able to tolerate a longer delay in obtaining them.

For handpumps and windmills, fast-moving spare parts include cup or cylinder leathers and wooden, steel, or fiberglass sucker rods. Since these parts are few in number and relatively inexpensive, these systems are less vulnerable to outages caused by a lack of parts than diesel engines, which require many fast-moving parts. Solar pumps typically do not require any fast-moving spare parts, although all pumping systems will occasionally require unexpected repairs. The parts needed to complete these repairs (e.g. a handpump head, windmill blade, or PV inverter) may only be needed every three, five, or ten years. However, when breakdowns occur, these spare parts should be available in local or nearby regional inventories, since it is highly unlikely that they can be fabricated locally under most circumstances in developing countries. The more fast-moving the part, the more widely it should be distributed. For example, diesel belts should be available at the local level, but pump cylinders or PV modules need only be available at the district or perhaps national level.

In some cases, parts may only be available from a central or regional, rather than a local, warehouse, so a longer period may elapse before repairs are completed. If so, the system designer and users must decide how they will meet water requirements until the system can be repaired. In some instances, especially if the part is very expensive and the number of systems being supported is small, it may be too expensive to maintain a regional inventory, so high-cost spare parts will have to be imported on an as-needed basis. (Avoid getting into this situation if at all possible. If one system is not supportable locally or regionally, use a different one that is.) If this is the case, it is essential that a communication and distribution network, including import agents and distributors, is in place already and that project planners, managers, and water users understand how much time is required to procure imported parts. One solution is to maintain a local inventory of at least one complete set of all spare parts for a system. These can be replaced as they are used.

For diesel, gasoline, and electric pumps, regular, high-quality supplies of fuel (diesel or electricity) and lubricants are of obvious importance. Fuel can vary by quality, seasonal availability, and cost:

- Diesel or gasoline may be of such poor quality or otherwise contaminated that it clogs engines, and electricity voltage may fluctuate so much that it can either burn out or simply be inadequate to run a motor.
- Fuel availability may vary due to lack of supply at the national level, regional shortages caused by unfavorable allocation schemes, or seasonal variations caused by, for example, impassable roads which prohibit hauling fuel during the rainy season.
- Costs may vary due to international price fluctuations, national or regional shortages, and imposition or removal of subsidies. In cases where the government controls allocation and price, users without access to reasonably priced fuel may have no choice but to procure fuel (and parts) on the black market at prohibitively high marginal costs.

Problems may also arise as a result of assigned responsibilities for provision of fuel. For example, in Sudan the government water agency is in principle responsible for supplying fuel to rural wateryards at subsidized rates. In reality, in communities without good political connections, the agency is often either unwilling or unable to provide fuel, and user groups are forced to buy fuel, parts, and the mechanics to use them on the local or regional black market. This requires them to pay twice for the same materials: once to the government water fee collector when people collect water, and again when the village water committee takes up its periodic collections to actually buy parts and fuel.

This emphasizes the importance of good system design to minimize both fuel consumption and other O&M requirements.

Available parts also can range greatly in quality. For example, in Indonesia there are three grades of PVC pipe, which vary considerably in quality and price. Buying the lowest grade is common practice. However, if not properly buried, it photo-degrades much more quickly than the better grades, and even when buried is much more susceptible to damage by trucks passing overhead than the higher quality pipe. This may result in the need for early and expensive replacement (digging under-road ditches is not easy). Another example is diesel engine parts. To repair Lister diesel engines, mechanics can use either authentic Lister parts or parts made by the many manufacturers (e.g., in India and China) who have essentially copied and locally produced the Lister design. These imitation parts are often much cheaper, but typically do not last nearly as long as the originals. You can minimize O&M by investing in higher quality system components and parts, and also by periodic inspections to detect minor problems (such as pipe leaks or bearings needing replacement) before they become major problems. This will help insure that things can be fixed before they deteriorate to the point where costly replacement becomes necessary.

Finally, standardization of system design, equipment, and components will facilitate O&M and help reduce costs. Standardization helps minimize the size of parts inventories, helps to insure that technicians will be available who are familiar with systems, and since parts can be purchased in larger lots from distributors, at least in principle makes individual parts cheaper to end users.

To get a clear picture of the possible difficulties in obtaining required spare parts and fuel for different equipment options, the questions below should be addressed when choosing systems:

- **Are all spare parts available locally at the pump site? List the name of local shop(s) or agent(s) and the types of spare parts they carry.**
- **How far is the nearest location outside the village where fast-moving spare parts for your pumpset are available? List the name of the village, the distance from the site, and the name of the shop or agent.**
- **Where do you have to go to get uncommon spare parts (usually the same location where full service and overhauls are available)? List the names of the agents and the spare parts and service they can provide.**
- **How long does it take to get spare parts when they must be ordered or imported?**
- **What arrangements have been made to deal with water shortages while waiting for parts and materials to arrive and the system to be repaired?**

9.2 Skilled Operators and Mechanics

The second category under O&M requirements is skilled personnel. The skills required to operate a pumping system are very different from the technical and diagnostic skills needed to ensure a long service life and proper repairs. Tasks for operators or caretakers typically include:

- starting and stopping the pumpset, as required;
- performing daily checks of fluid levels (where necessary) and equipment condition;

- handling limited preventive maintenance (e.g., tightening nuts and bolts), as the operator's training and authority and the available parts and tools allow; and
- contacting the proper authority to deal with specific problems, when needed.

Operators and caretakers are the most important human component in successful system operation. They form the first line of defense in the ongoing effort to keep a pumping system operational. Mechanics are necessary when the required maintenance or repair procedure is beyond the operator's authority or capability. Typically, mechanics must have:

- the ability to accurately diagnose problems in the system;
- the skills needed to make complicated repairs in the field;
- access to necessary tools to complete minor and major repairs; and
- mobility to travel to the pump site.

If individuals in the community possess repair skills, this will help assure that a broken-down system is returned to service promptly. Handpumps and windmills are most suitable for local repairs. Since the skills needed are fairly limited, people in the community can be trained to perform most maintenance and repair tasks. The widespread use of diesel engines for pumping water and generating electricity in isolated areas means that there are usually some area mechanics who are at least somewhat skilled. If the level of local repair capabilities is lacking, skilled personnel from outside the community are necessary to ensure that proper maintenance procedures are followed.

Solar pump repairs usually require specialized skills not normally found in rural areas. Individuals with basic skills in electricity may be available, but the specialized nature of PV technology may mean that suitable technicians will not be available even within the region. Although solar pumps rarely need corrective maintenance, it is still important to consider who will perform such repairs. If mechanics are available only regionally, you should also consider how far they may be willing to travel.

To determine the availability of qualified operators or caretakers and trained technicians, as well as their potential ability to handle maintenance and repair functions, you should answer the following questions.

Operators

- **Do the people nearby that might serve as potential operators or caretakers have any experience or familiarity with the equipment you are considering?**
- **Are there individuals with sufficient education and mechanical aptitude who could be trained to perform these functions well? If so, who could provide this training, and how much would it cost?**
- **Are operators likely to have the tools needed to operate the system properly and handle minor repairs?**
- **How much will operators need to be paid, and where will the money come from?**
- **Who will take over the operator's duties when the primary operator is not available?**

Mechanics

- **Are skilled mechanics and/or electricians available in the village who have general mechanical, engine-repair, and/or electrical skills?**
- **How far must skilled mechanics travel to assist with maintenance of the pumping system? How will they get there?**
- **Are mechanics from outside the community available year-round, or would transportation problems or other responsibilities make them unavailable at times?**
- **Can arrangements be made to provide training to mechanics and technicians so that the necessary skills are available when needed?**
- **How much will their services cost, how will they get paid, and where will this money come from?**

9.3 Transportation Networks

As long as spare parts, skilled labor, and/or fuel must be brought in from outside a village, the quality of the local and regional transportation network must be considered in equipment selection. Consider distance, travel time, the quality of roads and whether they are passable year-round, and the availability of vehicles or other means of transportation. For systems that have a high need for outside support, these are very important issues. That is why it is an advantage if skilled personnel and spare part and materials inventories are available locally.

Since the transportation network is critical in moving technicians, parts, and materials to a pump site quickly and efficiently, answer the following questions before choosing a system:

- **What means of transportation are readily available for travel to nearby towns or villages to obtain spare parts, fuel, or technical assistance—bus, official transportation, private vehicles, other modes?**
- **What distances must be traveled to obtain spare parts, fuel, and to summon mechanics?**
- **How long do these trips typically take?**
- **Are light- and heavy-duty trucks (four-wheel drive, if necessary) available to transport heavier equipment and spare parts to the site? If not, where can they be found?**
- **How much do these different means of transportation cost per kilometer or trip?**
- **Are fuel and parts for vehicles readily available on a year-round basis?**

9.4 Communication

Ineffective communication is an often overlooked factor contributing to long periods of system downtime. There are generally two types of communications problems—response time, and inaccurate or incomplete information. If it takes two days to summon assistance, every service requiring such communication requires at least two days plus the time needed for a response. In addition, because messages are often incomplete or inaccurate, maintenance and repair crews might bring the wrong personnel, parts, or tools. A simple message like "there is no water" is not very helpful to a maintenance crew that is trying to decide what spare parts and tools will be required. The crew may have to make an additional trip to get additional parts needed to complete the repair. The need for rapid, accurate communication of the nature of a problem to the proper person or agency is important in assuring a timely, appropriate response. One suggestion is that all site operators be given written forms (perhaps postcards) with the address and telephone number of the repair crew dispatcher, along with several questions which need to be answered when reporting problems. The following questions focus on important communication issues:

- **Are the proper steps for summoning maintenance and repair assistance clear to the operator/caretaker and users?**
- **Does the operator/caretaker have the training and skills to diagnose and report most basic problems accurately to the maintenance/repair crew?**
- **When outside assistance is needed for maintenance and repair, how is assistance summoned? Are these channels of communication open year-round? Do they depend on verbal, written, telephone, or radio messages?**
- **Is assistance requested from different sources, depending on the nature of the problem? If so, list the various types of problems and the corresponding sources of assistance, and make sure that operators or committees know that information.**
- **When assistance is summoned, how long is it likely to take to get a response from each source of help?**

9.5 Organizational and Financial Management

The ultimate authority and/or responsibility for a water supply system may rest with a local community leader or organization (such as the village water committee) or a regional or central government agency. When local persons or groups are responsible, they must have sufficient funds, organizational capability, and the capacity to mobilize resources to respond to problems, if they are to be successful. Responsibility without authority is meaningless. If a regional or central organization is responsible, it must be responsive to local needs for any maintenance and repair problems that cannot be handled at the local level.

Regardless of where the formal authority lies, some degree of community responsibility is always important in the successful operation of water supply systems. The choice of technology should take into consideration both the capacity of a village to be responsible for a pumping system and the availability of outside sources of periodic assistance. In general, less complex technologies such as handpumps are more suitable for situations where local authorities have responsibility for a system. More complex technologies that require higher levels of O&M support are more appropriate when responsibility for a system is more centralized.

For example, if care is taken in selecting a handpump, it is likely that most maintenance functions can be carried out locally. At the other extreme, most repairs of solar pumps must be performed by outside agents, who should be clearly identified prior to making a commitment to that technology. This does not mean that solar pumps are necessarily a bad choice; just that there must be responsive mechanisms for maintenance and repairs to ensure the long-term reliability of the system. Diesel systems usually require the largest ongoing commitment of resources because of the high engine O&M requirements relative to other technologies. Sometimes, a community will have a qualified mechanic available to perform maintenance, assuming that spare parts are available. Since the quality of local mechanics varies considerably, it is important to check thoroughly the experience of the person designated as a local mechanic. Sometimes, "repairs" can leave the system in worse shape than before. For the most part, windmills can be serviced locally, with the possible exception of changing the pump leathers.

To clarify the lines of authority and responsibility for your system, answer the questions below:

- **What person or organization has ultimate authority over the water supply system? Is this authority local or centralized?**
- **Does this person or agency control the financial resources necessary for successful O&M? If not, which organization does? Is obtaining funds a major problem for the community or user group when the need arises? Does any other group, in the private or public, formal or informal sectors, have the capacity to respond when problems occur? Are existing cost-recovery schemes (e.g., user fees) adequately enforced at the local level to ensure the availability of O&M funds when required?**
- **What group or individual in the community or nearby area has responsibility for the water supply system at the local level? Is the group or individual responsible to a local or central authority? Is the responsible party paid or a volunteer? Does it have other functions (e.g., village development or health) that may reinforce or get in the way of its responsibilities for the water system? If an organization is responsible, is it likely to represent a faction of the community or the whole village?**
- **Does this responsible party feel it can effectively bring resources to bear on operational problems when needed? If it must call on an outside organization for O&M assistance, will this other organization respond in a timely fashion?**
- **If there is a backup system or secondary water source, is it under the same authority as the primary system?**

The level of community participation in and management of a water system has been shown to have a large impact on O&M requirements and system sustainability. If people feel a sense of ownership and an ability to control their water system, they will probably take a more active support role in its financing, operation, maintenance, and repair. However, do not assume that people can do this without proper training. Successful system management includes financial management. In addition to keeping track of spare parts, materials, and tools, community water committees often are responsible for collecting and managing user fees, keeping account books on fee collection and expenses, and settling potential conflicts between users, factions within communities, or between communities and government water agencies. Developing a financial management plan is an important part of system planning. It should include discussion of and agreement on:

- How the system O&M is to be financed, which may include collecting user fees, soliciting donations or government support, or a wide variety of community-level revenue generation schemes.

- How user fees (if they are to be collected) will be set, collected, managed, and revised as the situation requires.
- How to deal with extraordinary expenses (such as a well collapse), the cost of which may far exceed accumulated user fees.

Record keeping is a critical component of community management. Plan to provide suitable training to communities so that they are capable of keeping good records, and actively encourage them to do so.

9.6 Points to Remember

Evaluating the capability of a maintenance and repair infrastructure is neither simple nor straightforward. It requires an assessment based on local conditions and the type of equipment being considered. In such an evaluation, there are several important points to keep in mind:

- Community participation in planning, installation (where appropriate), operation, maintenance, and cost recovery is often (if not always) of critical importance in assuring that proper O&M will take place.
- Local capability (e.g., for operation, maintenance, repair, and/or spare parts inventories) is always an advantage.
- Complex systems are likely to need more maintenance than simple ones.
- Well-known technologies and systems that are easily understood increase the possibilities for local repairs.
- The acceptable length of time for skilled technicians to get to your site with appropriate tools and spare parts depends on water availability requirements and backup sources of supply.
- If you are considering introducing new kinds of equipment into an area, maintenance functions should be integrated into the existing infrastructure, either government-operated or private, to the maximum extent possible. When possible, avoid trying to set up new organizations to support new types of equipment without substantial and long-term guaranteed financial support.
- Be sure to consider the need for and cost of ongoing training in O&M procedures and how the cost will be paid.

The questions given in this chapter are meant to encourage you to consider the most important issues related to operation and maintenance requirements for the equipment options under consideration. It is not important whether a spare parts warehouse is 20 or 60 kilometers away. What is important is whether the system designer, working with the beneficiary community and any other organizations who will have responsibility for maintaining the system, has come to an understanding about how to provide all the support necessary to keep the system up and running properly.

Overall, the questions given here are meant to give a sense of the complexity and potential difficulty of providing the necessary O&M support for the different system options. All too often, the importance of including consideration of proper O&M in the system design process has been overlooked. Many failed water systems spread throughout developing countries are testimony to this.

While it is impossible to guarantee that an existing maintenance and repair infrastructure will be responsive in the future to the O&M needs of the equipment you choose, careful consideration of answers to the questions listed in this section should give you a good indication of the likelihood for successful long-term, reliable operation of the system. The final section of this manual addresses the major remaining issue involved in pump selection—comparative costs.

Chapter 10: Cost Analysis

The first step in choosing a pump is to select several options that will meet the technical requirements at your site. The next step is to find out which of these options can be adequately supported by the O&M infrastructure in your area. This will probably reduce the number of suitable options. Finally, you need to analyze those options on the basis of Life Cycle Cost (LCC). Life Cycle Cost is the basis for an economic comparison called present worth (or present value) analysis. It takes into account all costs incurred over the useful life of your system, including those for the initial equipment and installation (installed capital costs), and those for operation, maintenance, and repair (recurrent costs).

10.1 Present Worth Analysis

While there are many kinds of comparative economic methods, present worth analysis is a convenient method for assessing the relative costs of different pumping systems. This method analyzes all costs associated with installation and use of a pumping system by adding the present worth of all costs for the system over its useful lifetime and calculating its Life Cycle Cost. Dividing the Life Cycle Cost by the discounted total volume of water pumped gives a unit cost for water, referred to here simply as **unit cost**. Calculating unit costs for two different pumping systems that are designed to deliver about the same volume of water from the same head allows you to make direct financial and economic comparisons between the two. This approach should be used to compare systems of approximately similar size. It does not address directly the question of benefits, so you cannot determine whether the benefits of the pump installation (in terms of increased health benefits or number of gardens irrigated, for example) will be worth the cost of the pumping system.

This chapter describes present worth analysis by discussing typical cost components (capital costs, recurrent costs for operation, maintenance, and repair), discussing the analytical method, and then taking you through examples showing how it is applied. The distinction between financial and economic costs is discussed, with an example that shows the difference between those two concepts. In general, a system's **financial** cost is determined from the user's viewpoint (how much the user actually has to pay to own and operate the system), while the **economic** cost is based on the perspective of the government or society as a whole (which may include such things as the real cost of subsidies). Since financial and economic unit costs can vary considerably, it is possible that selection of the most cost-effective system may depend on which perspective you take.

10.2 Types of Costs

Present worth analysis divides all system costs into two basic groups--installed capital costs and recurrent costs. The LCC is equal to the installed capital cost plus the present worth of all recurrent costs (see below). Installed capital costs are all assumed to occur at the start of a system's lifetime (i.e., at the beginning of Year One of the system's useful life). All later costs (e.g., for operation, maintenance, repair, and component replacement) are recurrent costs.

Present worth analysis is done not only to determine which system is cheaper to own and operate, but also to determine whether users will be able to afford it. To determine this, it is important to estimate all costs as accurately as possible, and then examine the cash flows needed to meet future recurrent costs. Some systems (e.g., diesel pumpsets) have low capital costs, but high recurrent costs. Others, such as wind and solar systems, have high capital costs, but low recurrent costs. Who will pay these different costs may have a significant impact on the choice of a system.

Typically, pumping systems in developing countries are **not** purchased with commercial bank loans which are then paid down over several years. Rather, they are usually paid for with cash. If a system is not going to be wholly dependent on outside funding (e.g., completely subsidized by the government or paid for by a donor organization), it is important to know what cost-recovery mechanism(s) will be used. Who will pay the installed capital costs? Will recurrent costs be funded by water-user fees? Are users willing and able to pay them? Up to how much? Will the government or some other funding source cover a fixed percentage of recurrent costs? Careful consideration of these questions is crucial when selecting a system, since an inadequately financed system will soon fall into disrepair.

A system's installed capital cost is the total of all equipment, materials, labor, and transportation costs incurred for complete installation of a system. Recurrent costs for operation, maintenance, and repair generally include:

- an operator's salary;
- wages for a mechanic to handle regular service and breakdowns;
- spare parts and replacement components;
- fuel, lubricants, and other consumable materials;
- transportation (including a driver); and
- overhauls, when necessary.

Recurrent costs can be subdivided into fixed annual, variable annual, and non-annual costs[1] which are discussed in more detail in the sections below. Each category can include costs for parts and materials, labor, and transportation. A matrix showing all the different types of system costs is as follows:

	Installed Capital Costs	Recurrent Costs		
		Fixed Annual	Variable Annual	Non-Annual
Parts & Materials				
Labor				
Transportation				

[1] In general, fixed annual costs, such as the pump operator's salary, are relatively constant costs which are independent of water output. Variable annual costs include items such as fuel and lubricants, which depend on how often the system is used. Non-annual costs, such as engine overhauls, may or may not occur in any given year.

When considering different types of system costs, it is simpler to consider only those costs which differ from one system option to the other. For example, if you were considering whether to use a diesel or a solar pump on a borehole, and both of the systems would use the same size borehole with the same diameter casing, there would be no need to include the cost of the borehole into the comparative analysis, since it would be the same for each of the systems. However, if you were comparing the costs of installing a small diesel engine versus several handpumps with the same total output, the diesel would only require developing a single source (borehole or open well). If, on the other hand, you needed to install four handpumps to meet the water demand, you might have to develop two or more sources (if you put two handpumps on each source). In this case, you should include the additional costs of source development in the analysis, since they would differ for the two system options. Depending on the particular systems under consideration, you may or may not need to include costs for components such as:

- well construction or drilling;
- field surveys;
- design work, including engineering drawings; and
- water storage tanks, which may or may not be needed for different systems and will vary in size depending on your type of system.

Where appropriate, these costs should be included in the matrix shown above. If the purpose of the analysis is to calculate water tariffs and 100% cost recovery, then **all** system costs must be included in the analysis. Sections 10.2.3 and 10.2.4 give detailed descriptions of how to estimate costs for each part of the matrix.

10.2.1 The Discount Rate

Discount rates are based on the concept of the time value of money. People put a higher value on money which is available now rather than in the future. Discount rates are a way of assigning a number to that higher value. For example, if a person is willing to forgo the use of $1 for one year to receive an additional ten cents, the discount rate is 10%.

The present worth of recurrent costs depends on the actual costs when they are incurred, and on assumptions about discount rate, inflation, and useful life of the system (also called the term of the analysis). The discount rate is used to calculate the present worth of future costs (for instance, the future cost of replacing a windmill cylinder after five years of operation). It is based on what economists consider the "opportunity cost," or the buyer's best alternative investment. If the best alternative is investing money in a bank at 10 percent interest, the assumed discount rate is 10 percent. This rate may vary for different investors, since deciding on the best alternative depends on personal circumstances and their willingness to take risks.

The discount rate you choose for your analysis should take into account the "real" opportunity cost of investing in a pumping system. This is the nominal discount rate (for example, 10% which you could get by putting your money in a Bank) *minus* inflation. Where countries have high inflation, the real opportunity cost can be much different than the formal (bank) discount rate. The opportunity cost for rural communities may have little connection with formal bank interest rates. For example, in many African countries, the best investment many rural people can make is in stock animals. It has been estimated that for a situation in rural Sudan[2], the nominal (not including the effect of inflation) opportunity cost of money invested in cattle is 18%.

Discount rates differ according to the user. You have to estimate the return on the best alternative investment given local conditions and users' perceptions. Individuals in the private sector may be reluctant to borrow money because of uncertainty about the future, in which case discount rates may need to be as high as 20-50 percent (or more, where inflation is rampant). For economic analysis, suitable rates are determined by government economists. The World Bank often uses economic discount rates of 10 to 12 percent. The discount rate can have a large effect on the results of analysis, particularly when competing alternatives differ markedly in their capital and recurrent costs. If there is some uncertainty about what discount rate to use, try several values and see what impact they have on the analysis.

10.2.2 The Term of the Analysis

Next, choose the term of the analysis. Usually, this is the same as the useful life of the major system component that will last the longest. For example, with solar pumps, the longest lasting (and most costly) component is the PV array, which has an estimated life of 20 years. Not all of the other components will last that long. They will have to be replaced periodically as they fail. The cost of repair or replacement for these components is included in the recurrent costs. For a diesel pump, the term of the analysis is the engine's useful lifetime. It can be overhauled several times, but eventually it will have to be replaced. To compare different systems you have to use the same term of analysis for all of them. For example, suppose you want to compare a solar pump and a diesel system. The term of the analysis for a solar pump is 20 years, and diesel engines in your area are expected to last only 10 years. You can still use this method by simply assuming that you replace the diesel engine at the end of the tenth year, considering its replacement as a recurrent cost. The term of analysis should be the useful life of the longest lasting major component of the system.

10.2.3 Equipment and Material Costs

In this section, ranges are given for typical capital and recurrent costs associated with the installation of each type of system. In some cases, these ranges are wide because of differences in capacity and in where the equipment is purchased and used. When possible, use cost information from local distributors in your area. The installed capital cost for a pumping system includes equipment costs for the power source and pump, other needed parts and materials, civil works (e.g., pump house and concrete engine pad), and associated labor and transportation costs. The power source could be a diesel engine, a solar array and controller, a windmill head with a tower, or a handpump head. Be sure to include the cost of all required accessories. Capital equipment costs can also include import taxes, duty requirements, and freight charges from the country of origin, but these should be kept separate for the economic analysis.

[2] *Consultancy Report for the Sudan Renewable Energy Project Water Pumping Program*, Ron White, ARD, April, 1989.

Diesel Systems

Costs for diesel engines are affected by the rated output, quality of the equipment, and location of the manufacturer. They range from US$100[3] to US$500 per rated kW. Other major items for diesel systems include:

- the pump and transmission, if any;
- pump houses and fencing, for security and protection of equipment and materials;
- other components for water storage and distribution, such as tanks, piping, and valves;
- under some conditions, the need for a more reliable system may involve purchasing a spare engine and/or pump; and
- a good water meter and pressure gauge should also be purchased for diagnostic purposes.

In addition to these more expensive components, lower cost items needed to install a system can add up to a total that is a significant portion of the overall equipment and materials cost. They include engine frames, foundation bolts, non-return valves, pipe unions, gate and pressure-relief valves, spare pulleys, belts or drive shafts, and some basic tools for operator servicing. Required materials also include cement, sand, gravel, reinforcing mesh, and/or "re-bar" to make a concrete foundation for the engine (or windmill tower, solar array's mounting frame, or handpump base), as well as fencing. These can often amount to 10 percent of the equipment's total capital costs. A complete list of parts and materials for each of the four system types is given in Appendix E. Typical costs for diesel pumping systems are given in Table 6.

Table 6
Typical Capital Costs for Small Diesel Pumping Systems*
(in US $)

Diesel engine (2 to 10 kW)**	$600-4,000 (small/Indian–large/Lister)
Pump (complete)	$500-3,000 (Mono–Jack pump)
Civil Works (pad, pump house)	$500-1,000
Other (valves, fuel tanks)	$1,000-3,000
Total System Cost (CIF***)	$3,600-11,000

*Costs for diesels are based on typical 1990 costs in Southern and East Africa. In addition, water storage tanks range in price from about $1,500 to $10,000, depending on their size (between 5 and 30 m^3), construction (fiberglass, steel, or lined steel), and whether they are elevated to pressurize the distribution system. Towers add considerable expense.

**Smaller engines (2-4 kW) are much more expensive per rated kilowatt than larger ones.

***Cost/insurance/freight (delivered price)

[3] The lowest cost Indian-made copies of the popular Lister 8/1 diesel rated at 6 kW cost only US$600, or $100/kW as of mid-1990. All costs in this chapter are as of 1991, unless otherwise stated.

Solar-Powered Systems

For solar pumps, PV modules are the most expensive component. Other system components include the pump, motor, array support structure, wiring, and controller and/or batteries. Array costs are about \$5.50 per W_p, from the point of manufacture (as of 1992). This cost can easily rise to US\$9/W_p or more where distribution and shipping costs are high. In most cases, motors and pumps for a solar system are purchased together because solar pump manufacturers design and match pumps and motors to maximize subsystem efficiency. Controller costs vary considerably depending on the type of control system chosen and the country of manufacture. Some manufacturers may specify controllers that are designed to operate with their systems. Array support structures cost from US\$100 to US\$200 for racks that hold four to six modules. Wiring costs are usually US\$50 to US\$200. Unlike diesel pumps, neither PV nor wind systems normally require pump houses, but all three require fencing.

Table 7
Typical Costs for Solar Pumping Systems
(in US \$)*

PV Array (0.6-1.5 kW_p @ \$6/W_p)	\$3,600-9,000
Civil Works (pad, fencing)	\$300-1,000
Mounting Racks (stationary/tracking)	\$500-2,400
Other (wiring, rods, meters, pipe)	\$200-700
Plus one of the following two pumpset configurations:	
Submersible Pumpset (including motor, pump, and inverter/controller)	\$2,750-3,500
or (these custom systems are much less common):	
Motor (0.5-2 kW)	\$200-800
Pump (only, no submersible motor)	\$200-700
Controller	\$200-1,500

*These costs were supplied by Tim Ball of Solar Engineering Services in Olympia, Washington, and are for standard commercial systems (e.g., Grundfos or MacDonald submersible pumps with fixed or tracking arrays). These costs are current as of Spring, 1992.

Thus, for a standard commercial solar system with a 1.5 kW_p array which can pump about 30 m^3/day at 25-30 meters head, a submersible pumpset with controller/inverter, all other required parts and materials, plus installation labor, the total system cost is around \$13,000, or \$8.60/W_p installed. This does not include a tracking array, which would deliver more water (20-30% more, depending on the site conditions) but would cost another \$1,600.

Wind Systems

Windmill and tower costs are highly dependent on shipping charge· as these machines tend to be heavy. In general, units are supplied complete, with no additional or optional parts to be considered. The cost for a windmill is higher for those with larger rotors. The range of costs is US$200 to US$500 per square meter of rotor area. Simpler designs that are fabricated locally or regionally are less expensive than imported American or European windmills of similar size, but depending on design and manufacturing quality, locally-made windmills may not have the same durability and performance as imported ones. Tower costs are proportional to height and to the quality of construction; they range from US$1,000 to US$3,000, depending on whether the tower is made locally or purchased and imported with the windmill. Cylinder costs are often dependent on design and materials, with high-quality, ball-valve cylinders being more expensive than those with flap or spool valves, and stainless steel much more expensive than standard brass. Other items include the drop pipe, pump rod, pipe clamp at the wellhead, cement for the foundation, and fencing.

Table 8
Typical Capital Costs for Wind Pumping Systems
(in US $)

Windmill head (2 m-6.4 m diameter rotor)	$1,000-8,000
Tower and associated hardware (5-15 m height)	$1,500-4,000
Pump cylinder with spare leathers	$250-800
Civil Works and Other (foundation, tank, piping)	$1,000-3,000
Total System Cost (CIF)	$3,750-15,800

Handpumps

Handpump costs vary considerably depending on the country of origin. You might assume that locally fabricated units would be the least expensive, but this is not always the case because mass-produced units (such as the India Mark II) may be cheaper than small local production run units. Handpump costs range from US$300 to US$1,000. The very promising Afridev VLOM pump is manufactured in Kenya, Malawi, and several other developing countries, and sells for about $500.

Table 9
Typical Capital Costs for Handpump Systems
(in US $)

Handpump head	$300-1,200
Pump cylinder with spare leathers	$100-400
Pump rod (depends on depth and material)	$30-500
Other (foundation, drain, piping)	$100-400
Total System Cost (CIF)	$530-2,500

For all four types of systems given above, besides equipment and materials, capital cost also includes the labor and transportation associated with installation. Labor costs are often divided into skilled (e.g., diesel mechanics or electricians), semiskilled (e.g., masons), and unskilled components (common laborers). This is partly because the daily or hourly rates are different for these groups and because the unskilled portion is often valued below the wage rate in the economic analysis (see Section 10.4). You should get some idea of labor costs or daily rates for these three groups, including any relevant per-diem or other allowances. Remember to include the preparation associated with collecting tools and equipment in your estimates for installation time.

Time Required for Installation

Assuming that the well is already developed, the minimum amount of time required for installation of a diesel pump is about three to five days and includes pouring a foundation, lowering the pump, drop pipe, and pump rods, installing the engine, and building a prefabricated metal pump house. Solar pumps often take a bit longer but should require no more than six to seven days, unless the crew is very inexperienced. For the first few installations of any system, the need for on-the-job training will increase installation time somewhat. Windmill installation can easily take up to 10-12 days in typical developing country situations. Handpumps can typically be installed in two to three days, if all goes well. These figures are only for pump installation, and do not include any time for well development. They should be used only as general guidelines for estimating the actual time needed for an installation at your site[4]. Your estimate will depend on the number of people in an installation crew as well as on their training and familiarity with the particular type of system being installed. The size of a typical crew varies from three to ten, of which one to three are usually skilled laborers.

Transportation Costs

Transportation costs are affected not only by the distance to the site, but also by the type of vehicle used and the number of trips. It may be necessary to make more than one trip to the site to move all the equipment, gear, and personnel needed to complete the installation. Thus, the total transportation distance can easily be two to three times the round-trip distance from the installation center to the site. The type of vehicle(s) affects transportation costs because light, two-wheel drive trucks are less expensive to operate and maintain than heavier four-wheel drive vehicles and trucks, which may be needed for some installations such as windmills. To get some idea of transportation costs, talk to vehicle rental agencies or truck users in the private sector. Often it is possible to get a daily rental figure plus a mileage charge, which will probably not include fuel costs. Rental agencies usually have a good estimate of typical fuel use per kilometer.

Once these cost components for equipment, materials, labor, and transportation have been calculated separately, they are added together to determine the installed capital cost. All other system costs associated with operation, maintenance, and repair are recurrent costs.

[4] While all of these estimates may seem much larger than strictly necessary, they are based on experience with many systems in several representative countries, and also include transportation and set-up time. Note that for all installations, it is best to wait several (2-3) days for the concrete to cure properly (to maximize its strength) before installing any hardware.

10.2.4 Recurrent Costs

As mentioned above, recurrent costs can be divided into fixed annual, variable annual, and non-annual costs. This section discusses these cost components for all four system types.

Fixed Annual Costs

Fixed annual costs for a pumping system are annual recurrent costs that are not affected by the amount of use a system receives. Fixed annual costs do not fall neatly into the materials, labor, and transportation categories used above. Rather, they include such items as **overhead, finance charges** (e.g., interest on a loan used to buy the system), and **labor costs for an operator** (assuming a flat monthly salary with no overtime), if any. For example, fuel is not a fixed cost since it depends on how much the engine is run.

Whether or not there are overhead costs and how high they are depends on the way a pumping system is managed and maintained. Overhead can include costs for things such as record-keeping or for maintaining a vehicle, office, warehouse, spare parts inventories, or headquarters staff. These costs are often omitted from comparative analysis on the assumption that they will be similar regardless of the system chosen, but this is not necessarily the case. If a system was paid for with cash from business operating funds, personal monies, or a grant, there will be no interest charges. Systems with greater O&M requirements will require more management time and much greater bookkeeping.

The labor cost for an operator is usually a fixed cost that depends on the type of pump and daily average use of the system. It rarely changes with hourly usage of the pump each day. For example, diesel pumps are often run by a full-time salaried (i.e., not hourly) operator. In instances where the operator may have additional unrelated responsibilities (e.g., a maintenance person for a school or a driver), the allocation of some time to non-pumping activities can reduce labor costs somewhat. Handpump operation does not require an actual operator. However, it is important to value the time spent pumping water in the economic analysis. Typically, this time is costed at the prevailing wage rate for unskilled labor.

Variable Annual Costs

Variable annual costs include **all materials (i.e., fuel, oil, and parts), labor (except for the operator), and transportation required for normal operation, servicing, and repair of the system.** These are all the items whose use depends on the amount of time the system is operated during the year. Estimates for these costs can be made by modifying the information provided in Chapters 5 through 8 to meet the specific conditions at your site. These requirements and their associated costs are summarized here.

Annual labor costs are a function of the number and duration of trips made in response to normal service requirements and breakdowns, as well as the crew size and skill levels. Of the four systems considered here, diesel pumps probably will require the most maintenance and repair trips. For planning purposes, count on at least four such trips per year up to as many as one per month, depending on the situation. For solar, wind, and handpump systems, the number of maintenance/repair trips will probably be many fewer (about one to three annually) if the installation is properly done. Fewer trips may be needed if the pump operator can perform some minor servicing.

Maintenance and repair crews typically consist of a mix of skilled, semiskilled, and unskilled labor. In estimating annual labor costs for service and repair, consider the specific skill mix required for your system. In the absence of other information, assume that a repair crew of three—one skilled and two unskilled—plus a driver will be sufficient to deal with 70 percent of all necessary repairs. Larger crews of as many as eight will be needed for jobs like pulling pipe, replacing engines, or repairing breaks in the pipeline. Labor costs can then be estimated by calculating the total daily wage rate for smaller and larger crews, and then multiplying by the number of days required for each crew. Remember, if all labor arises from salaries included in the overhead figure discussed above, you need not calculate labor costs here.

Annual transportation costs include trips made for service and repair, as described in the preceding paragraphs. In addition, they should include trips to deliver fuel, lubricants, and other parts and materials for diesel systems. The cost of such trips will depend on the distance and the type of vehicle used. The distance traveled may or may not be the same as the installation distance—it depends on the relative locations of service facilities and the pump site. It is advisable to combine trips (e.g., regular servicing and a delivery of diesel fuel) as much as possible to minimize costs.

The type of vehicle used will depend on what is available, plus the requirements of the job and the condition of the roads to the pump site. Of course, lighter vehicles should be used when possible, but this may not always be practical given other constraints. Vehicle charges are often given as a daily rate plus a mileage charge plus fuel. If the cost of vehicles is figured into the overhead, the variable annual transportation costs should be reduced or eliminated. Typically transportation costs range from US$0.25 to US$1.00 per kilometer.

Non-Annual Costs

Non-annual costs are those that do not necessarily recur every year. These costs are treated differently because of their intermittent nature. They include such items as major or minor overhauls for diesel systems, or the replacement or repair of any major system component.

For diesel systems, non-annual costs include the overhaul or replacement of the engine, pump, and down-hole components, as necessary. Non-annual costs for solar pumps include the overhaul or replacement of batteries, controllers, electric motors, pumps, and other down-hole equipment, as well as the replacement of solar modules in case of vandalism or theft. For windmills, non-annual costs will likely be limited to the replacement of the pump and down-hole components—the drop pipe, sucker rods, leathers (if these are not replaced annually), and pump cylinder. There may be a need to repair or replace the rotor or windmill head, but this should not happen on well-designed, properly installed systems. The only non-annual costs for handpumps will probably be the replacement of the down-hole components and possibly the pump-head or bearings. For all systems, other non-annual costs may include the repair or replacement of civil works, storage tanks, fences, pump houses, and wells (particularly if hand-dug wells are used).

Estimates of recurrent costs for the four types of systems considered in this manual are given in Tables 10 to 13.

Table 10
Recurrent Costs for Diesel Pumps
(in US $)

Fixed Annual	
Interest on loan	if applicable
Pump operator	varies considerably: $200-1,500 (Sudan-Botswana)
Variable Annual	
Diesel fuel/lubricants	varies depending on use: $200-800
Parts and materials:	
Oil and filter changes (monthly)	1 day of labor + $5-15 each
Minor repairs (3-6 times annually)	1 day of labor each + $10-100
Mechanics for maintenance/repairs	$250-750 (not including overhauls)
Non-Annual	
Engine overhaul	every 2 to 5 years, $200-1,000
Replace/repair pump and/or pipes	every 5 to 10 years (see engine/pump cost)

Notes: Fixed costs must be determined based on local practices and specific site conditions. Fuel costs can be calculated using the method given in Chapter 5. The oil and filters may need to be changed more or less often depending on engine use and operating conditions. For an engine that is used eight to nine hours a day, the oil and filters should probably be changed once a month. Repair costs are highly variable and will be affected by the quality of preventive maintenance and repairs. Engine overhauls and repair or replacement intervals for the pump and piping are also highly variable depending on the type of engine, quality (and hence cost) of replacement parts, distance to the maintenance yard (if not performed on-site), and who does the overhaul (private or public sector mechanics). The values shown are indicative of average conditions in developing countries.

Table 11
Recurrent Costs for Wind Pumps
(in US $)

Fixed Annual	
interest on loan	if applicable
pump caretaker, if any	varies: $0-500
Variable Annual	
replace leathers and oil or grease	1 day of labor + $5-15
repair 1 to 4 times annually	1 day of labor each + $0-100
Non-Annual	
replace cylinder and pipes	every 5 to 10 years: $400-1,000

Notes: Depending on water quality and the extent of pump use, leathers may need to be replaced more often than annually. Other repairs may be required more or less often depending on the quality of the installation and the users' care of the windmill. The replacement interval for the pump cylinder, sucker rods, and piping will depend largely on water quality. If the water has highly aggressive or abrasive characteristics, the cylinder and pipes will have to be replaced often, perhaps even more often than indicated in the range. Based on detailed studies in Botswana and Sudan, annual recurrent costs for properly maintained windpumps range between $80 and $400

Table 12
Recurrent Costs for Solar Pumps
(in US $)

Fixed Annual	
interest on loan	if applicable
pump caretaker, if any	varies: $0-500
clean array, check wiring	1 hr of labor per week
Variable Annual	
replace leathers (for piston pumps)	1 day of labor + $5-15
minor repair 1-2 times annually	1 day of labor each + $0-300
Non-Annual	
repair or replace motor/pump	every 3 to 10 years: $250-2,000
repair or replace electronic parts	every 3 to 10 years: $100-1,500
replace cylinder (if any) and pipes	every 5 to 10 years: $400-1,000
Replace any broken PV modules	total varies greatly, but about $350/module

Notes: Predicting the long-term frequency of repairs and replacement for solar pump components is difficult because few systems have been in operation for more than ten years. Many early units required the replacement of major components every year or two, particularly for electrical components such as controllers, inverters, and motors. Newer units have overcome those early problems, and much longer component lifetimes are common. Minor annual repairs consist primarily of replacing poor electrical connections or vandalized modules, if necessary Vandalism varies tremendously from country to country, and even among communities in the same area. Solar pump annual recurrent costs are about $250 annually, assuming (based on field experience) that one PV module needs replacement every other year due to vandalism.

Table 13
Recurrent Costs for Handpumps
(in US $)

Fixed Annual	
interest on loan	minor, if applicable
pump caretaker, if any	varies
Variable Annual	
replace leathers	1 day of labor + $5-15
repair 1 to 4 times annually	1 day of labor each + $0-100
Non-Annual	
repair handle/replace bearings	every 1 to 4 years: $25 -$50
replace cylinder, pipes, and rods	every 5 to 10 years: $200 - $800
replace pump-head	every 5 to 10 years: $200 - $1,000

Notes: Generally, the maintenance and repair requirements for handpumps will be easier to meet, and costs will be lower if the drop pipe does not have to be pulled to replace the leathers or fix the cylinder. Handpumps designed using the VLOM concept will have fewer needs for more expensive repairs by personnel from outside the immediate area. High transportation costs due to centrally located maintenance units can drive recurrent costs quite high. Annual recurrent costs range between $24 and $300.

10.2.5 The Cost Matrix

The cost matrix for capital and recurrent costs shown at the beginning of this section should be completed based on the information given above. Two matrices will be necessary if a financial and an economic analysis are carried out. Differences between the two are discussed in Section 10.4 below.

Note that for the sake of simplicity, inflation of specific costs over and above the general rate of inflation has not been discussed in this section. While it is true that any or all of the costs discussed here can change (increase or decrease) at a rate different from the general rate of inflation, it is often very difficult to predict the magnitude (or often, even the direction) of those changes. If you have information which convinces you to believe that one or more of the recurrent costs of your system will change over the period of the analysis, factor that information into the analysis. Better yet, make several calculations of the unit cost using different assumptions about the change in one or more variables. This "sensitivity analysis" will allow you to see what effect your assumptions have on the unit cost.

10.3 Present Worth Analysis

This section discusses the analytical method for present worth analysis. It requires that all future costs be discounted to their present worth. This is accomplished by grouping costs so that simple formulas can be used to calculate the present worth of each group. A list of all relevant formulas used in present worth analysis is provided in Appendix F. This method is not as complicated as it initially might seem in the explanations below. Look carefully at the examples to see how it is done.

The present worth of a specific cost depends on when that cost is incurred (paid). If a cost is incurred in the future, it will be discounted (see below) to the present by calculating its present worth. The method assumes that everything begins at the start of Year One, and each year's recurrent costs are paid at the end of each year. Since the analysis begins when the system is installed, the installed capital cost (incurred at the beginning of Year One) does not need to be discounted as do future costs.

Example 18: Discounting a Single Future Payment

If the discount rate is 10%, what is the present worth of a pump cylinder costing $300 which will have to be purchased in Year Five?

To calculate the present worth of a single future cost, use the following formula:

$$P = F(1 + d)^{-n}$$ ***(Formula #15)***

where P = present worth of a future cost

F = future cost

d = discount rate, in percent

n = year of occurrence for the future cost

Therefore, the present worth of the cylinder is:

$$P = 300(1 + .10)^{-5} = 300 \times 0.6209 = \$186$$

(continued on next page)

Example 18 *(cont.)*

Note that the present worth of any future cost will always be less than the actual cost.

Alternatively, you could look up the F1 factor for calculating the present worth of a single future payment (or cost) on the Compound Interest Factors Table in Appendix F. First, move across to the double (F1 and F2) column for a 10% discount rate. Then look down the F1 column until you find the factor F1 = .6209 corresponding to N = 5 years in the leftmost column. Then,

P = 300 x F1 = 300 x .6209 = $186.

You can use this formula to calculate the present worth of any non-annual costs. For each occurrence of a non-annual cost, Formula 15 should be used to calculate its present value. It should also be used to calculate the present worth of individual total annual costs if they vary from year to year over the term of the analysis (i.e., if pump operation varies from year to year). Fixed and variable annual costs for materials, labor, and transportation should be combined to get a total for annual recurrent cost. This will be the same for each year of the analysis, if the equipment is operated for the same amount of time every year. Use Formula 16 to calculate these costs:

$$P = A \times \frac{(1+d)^N - 1}{d \times (1+d)^N}$$

Formula #16

where P = present worth of a uniform series of future costs

A = annual cost or payment

d = discount rate, in percent

N = term of the analysis in years

To simplify this calculation, refer again to the Compound Interest Factors Table given in Appendix F to find the correct factor (F2) to calculate the present worth of a uniform series of future payments. Just find the value of F2 for the number of years and the discount rate you are using, and multiply it by the value of the fixed annual cost. Example 19 shows how this is done.

Example 19: Discounting a Series of Future Payments

What is the present worth of a series of equal payments of $1,000 each, which will be paid for a pump operator's salary over a 15 year period at a discount rate of 6%?

From the Compound Interest Factors Table in Appendix F, the F2 factor for 15 years at 6% is 9.7122. Therefore, the present worth of that series of payments is:

P = A x F2 = $1000 x 9.7122 = $9,712

Example 20 below shows how these discounting procedures can be used to find the present worth of recurrent costs for a pumping system. Note that this example does not consider the amount of water pumped, nor was a unit cost calculated. This procedure will be shown in the example in the Section 10.5.

Example 20: Calculating Present Worth

Assume that the discount rate is 12 percent over the 20-year term of this analysis. The following table shows expected costs over the life of the pumping system you are considering. Of the non-annual costs shown, the first (totaling $1,150) occurs in year 10. The second ($625) occurs in years 5 and 15. What is the total present worth of these recurrent costs?

	Installed Capital Costs	Recurrent Costs			
		Fixed	Variable	Non-Annual	
Parts & Materials	3,000		750	1,000	500
Labor	500	1,000	100	100	75
Transportation	300		50	50	50
Total	3,800	1,000	900	1,150	625

The present worth of installed capital costs is $3,800. The present worth of fixed and variable (here assumed to be constant) annual costs is given by Formula #16:

$$P = A \times \frac{(1 + d)^N - 1}{d \times (1 + d)^N}$$

Substituting values from the cost matrix above:

$$P = (\$1{,}000 + \$900) \times \frac{(1 + .12)^{20} - 1}{.12 \times (1 + .12)^{20}} = \$1{,}900 \times 7.47 = \$14{,}192$$

Alternatively, look up the appropriate value of F2 in Appendix F: 7.4694. Multiply $1,900 (from above) by 7.4694 to get $14,192.

The present worth of each of the three non-annual costs must be calculated separately.

At year 5: $P = \$625 \times (1 + .12)^{-5} = \$355$

At year 10: $P = \$1{,}150 \times (1 + .12)^{-10} = \$370$

At year 15: $P = \$625 \times (1 + .12)^{-15} = \$114$

Alternatively, look up the appropriate F1 values for these three calculations in the Compound Interest Factors Table in Appendix F. At 12%, for:

Year 5: F1 = 0.5674, so $P_1 = \$625 \times 0.5674 = \$355$

Year 10: F1 = 0.3220, so $P_2 = \$1{,}150 \times 0.3220 = \$370$

Year 15: F1 = 0.1827, so $P_3 = \$625 \times 0.1827 = \$114$.

Therefore the total present worth of all the costs of installing, operating, and maintaining this system (in other words, its Life Cycle Cost) is:

$3,800 + $14,192 + $355 + $370 + $114 = $18,831.

10.4 Financial Versus Economic Analysis

The basic difference between financial and economic analysis is one of perspective. Financial analysis relates to private costs and benefits, while economic analysis is concerned with social costs and benefits to a community or nation. Usually, the private sector is more concerned with financial analysis. Analysis done to address public sector needs is often economic. Whether you should perform one or both depends on whom the pumping system will serve, who is paying for it, and the purpose of the project behind it. If you want to do a detailed economic analysis, you may want to discuss some of the details of the analysis with a government or World Bank economist.

The major difference in calculating financial and economic present worth is making allowances for factors that have social impact, such as:

- foreign exchange costs (where the local currency is not openly traded at market rates);
- interest rates and loan charges (where loans are taken out to buy equipment, or where user fees are invested in sinking funds to finance future recurrent costs);
- taxes and subsidies varying between one kind of equipment or fuel and another;
- regulated prices for materials (such as steel for manufacturing windmills or pumps) or energy (diesel fuel, gasoline, or electricity);
- employment generation (which is in the best interest of the government to encourage); and
- training costs (which may or may not be borne directly by recipients or beneficiaries of the training).

These allowances are commonly reflected by what are called shadow prices. For example, in most developing countries, the economic cost of labor is less than the actual financial cost. This means that when there is a labor surplus (in most developing countries, this pertains only to unskilled labor), the economic cost to the country or society as a whole is less than the market price or current wage level. Shadow prices are used to reflect the difference between the market price and the true value of goods, services, and other production factors. The shadow price for unskilled labor is a multiplier (usually between 0.4 and 0.7) that decreases the actual cost of unskilled labor in an economic analysis. Its value is usually determined by government economists and planners, and reflects the government's interest in increasing employment, especially for unskilled labor.

In some countries, foreign exchange costs and real interest rates do not reflect true economic costs. This is evident in the large differences frequently seen in official versus free market exchange rates. Interest rates used in economic analysis may be dictated by government economists and, thus, may not necessarily reflect the true cost of borrowing capital. In addition, the export earnings of some countries are based on the depletion of resources (e.g., mining). In these cases, funds may be available for import purchases in the short run, but not over the longer term as foreign earnings decline. Circumstances such as these lead to shadow pricing for foreign currency requirements to better reflect the real cost of foreign exchange expenditures. Such shadow pricing typically increases the cost of imported items by 5 to 15 percent (i.e., a shadow price on foreign exchange of 1.05-1.15).

From the standpoint of a private user or business person, taxes are part of the cost of doing business, and any government subsidy is considered a benefit. These costs and benefits may be significant enough to influence some activities in the private sector. However, from the government's perspective, they do not represent costs or benefits at all, but merely an internal transfer of money and control over resources. Economic analysis does not include either taxes paid as costs, or subsidies as benefits. Actually, taxes and subsidies are often used as mechanisms to help manipulate private sector activity to bring it more in line with what the government believes is the greater national good. Interest paid on domestic loans and depreciation allowances also fall into this category of transfer payments and, hence, are included in financial but not economic analysis.

When the economic cost for labor is less than the financial cost, labor-intensive systems—those with proportionally higher labor requirements—become more attractive than capital-intensive ones from an economic perspective. For instance, this means that the unit cost of a diesel system, which has a higher proportion of labor costs and lower proportion of capital costs than other systems, is lowered by the shadow-pricing of unskilled labor. Similarly, the unit costs of capital-intensive systems such as wind or solar are increased when foreign exchange is shadow-priced at a value greater than 1.0.

Training costs incurred by firms in the private sector are seen as financial costs of doing business. Private businesses train individuals with the expectation of benefitting from their employees' increased skills and ability. However, since employees do not always remain with the firm providing the training, benefits may not always accrue to those firms. This constitutes a disincentive to the private sector to provide training. In most countries, development of a more highly skilled work force is a clearly stated government goal. Training costs may not be considered in an economic analysis, if the benefits of a more skilled work force are considered to be equal to or greater than the financial cost. Private sector training costs may be shadow-priced to reflect potential economic benefits. Example 21 shows the effect of shadow-pricing on economic analysis.

Example 21: Economic Life Cycle Cost

Using the information given in Example 19, calculate the economic LCC for that system. The shadow price of unskilled labor is one-half of the financial price. Assume that half of the labor cost is unskilled. All equipment and materials are imported. The transportation cost is also shadow-priced, since trucks, fuel, tires, and all spare parts must be imported. The shadow price on foreign exchange is 1.15. What is this system's Life Cycle Cost?

First, determine the economic cost entries for the matrix given in Example 19. Multiplying the financial values of various costs by appropriate shadow price multipliers gives:

	Installed Capital Costs	Recurrent Costs			
		Fixed	Variable	Non-Annual	
				Year 10	Years 5, 15
Parts & Materials	3,450		863	1,150	575
Labor	375	750	75	75	56
Transportation	345		58	58	58
Total	4,170	750	996	1,283	689

(continued on next page)

Example 21 ***(cont.)***

Again, the first non-annual recurrent cost listed ($1,283) occurs in year 10. The other ($689) occurs in years 5 and 15. The present worth of installed capital costs is $4,170. The present worth of fixed plus variable (here assumed to be constant) annual costs is given by Formula #16 (or by using the appropriate F2 factor):

$$P = A \, x \frac{(1+d)^N - 1}{d \, x \, (1+d)^N}$$

Substituting values from the matrix gives:

$$P = (\$750 + \$996) \, x \frac{(1+.12)^{20} - 1}{.12 \, x \, (1+.12)^{20}} = \$1{,}746 \text{ x } 7.47 = \$13{,}042$$

The present worth of each of the three non-annual costs must be calculated separately using Formula #15 (or the appropriate F1 factor from Appendix F).

At year 5: $P_1 = \$689 \text{ x } (1 + .12)^{-5} = \$391$

At year 10: $P_2 = \$1{,}283 \text{ x } (1 + .12)^{-10} = \$413$

At year 15: $P_3 = \$689 \text{ x } (1 + .12)^{-15} = \$126$

Therefore, the present economic worth of all costs (i.e., the system's life-cycle cost) is:

$4,170 + $13,042 + $391 + $413 + $126 = $18,142

The financial and economic present worth calculated in Examples 20 and 21 do not differ appreciably, partly because the increased economic cost of the imported equipment and materials was largely offset by reduced economic cost of labor. The economic cost is slightly less (US$689). In other circumstances, however, these two costs can vary considerably. When comparing different system options, one may be cheaper economically and the other financially[5]. In that case, the choice of a system would depend on the perspective of the potential purchaser.

10.5 Unit Cost of Water

Finally, the unit cost needs to be calculated, which depends on the amount of water pumped. The unit water cost is the Life Cycle Cost of installing, operating, maintaining, and repairing the system divided by the volume of water it pumps (in cubic meters) each year over its useful lifetime. The economic unit cost is determined by dividing the system's life cycle cost by the total discounted water output over the system's useful life, as shown in Example 22.

[5] This is especially true where one system is relatively labor intensive (like diesels) and the other is relatively capital intensive (like wind or solar pumps).

Example 22: Calculating Economic Unit Cost

Calculate the unit cost of water for the system described in Examples 19 and 20, assuming that the daily water demand in Year One is 24 m^3/day. Calculate the discounted water value, where:

Discount Rate = 12.0%
Annual Demand Increase = 3.0%

Year	Daily Demand (m^3)	Yearly Demand (m^3)	F1 Factor (see Appendix F)	Discounted Water (m^3)
1	24.0	8,760	0.8929	7,821
2	24.7	9,023	0.7972	7,193
3	25.5	9,293	0.7118	6,615
4	26.2	9,572	0.6355	6,083
5	27.0	9,859	0.5674	5,595
6	27.8	10,155	0.5066	5,145
7	28.7	10,460	0.4523	4,732
8	29.5	10,774	0.4039	4,351
9	30.4	11,097	0.3606	4,002
10	31.3	11,430	0.3220	3,680
11	32.3	11,773	0.2875	3,384
12	33.2	12,126	0.2567	3,112
13	34.2	12,490	0.2292	2,862
14	35 2	12,864	0.2046	2,632
15	36.3	13,250	0.1827	2,421
16	37.4	13,648	0.1631	2,226
17	38.5	14,057	0.1456	2,047
18	39.7	14,479	0.1300	1,883
19	40.9	14,913	0.1161	1,732
20	42.1	15,361	0.1037	1,592
TOTAL DISCOUNTED WATER =				**79,109**

Then, since the LCC of the system was calculated to be $18,142, to get the Unit Cost, divide by the Total Discounted Water as follows:

$$\text{Unit Cost} = \frac{18{,}142}{79{,}109} = \$0.23 \text{ per cubic meter}$$

This final value, the economic unit cost of water over the system's useful lifetime, is the figure you should use to compare this system with other options. If you are designing systems for private users, you should use this same basic procedure, but calculate the financial unit cost instead.

When evaluating the LCC and unit costs of different technology options, several other points should be considered:

- International donors are more likely to be able to provide funds to cover high installed capital cost systems than are private individuals or host governments.
- Host governments are sometimes not even able to cover recurrent costs, even if the installed capital cost is covered by a donor.

- Governments may or may not be able to justify higher capital costs to benefit from lower life cycle costs, because of short-term monetary constraints.
- In most places, private sector purchases are very sensitive to initial capital costs, such that low capital costs often influence the choice of technology regardless of the potential for life cycle cost savings.

It is important to make one final point in this section on comparative costs. If you are considering introducing a type of pumping system that is unfamiliar locally because it has the potential for long-term cost savings, remember that simple cost parity is not enough to convince potential buyers to adopt a new or unfamiliar type of system. There would probably have to be a significant price difference to get potential users even to consider the new system. Just as with any other investment, people must be motivated by profit to take a risk.

For example, if you are considering solar or wind pumps in an area that has historically used only handpumps or diesel systems, buyers are not likely to purchase unfamiliar systems simply because they are equal or slightly cheaper in cost than conventional systems. There would probably have to be substantial savings associated with using the new systems to make it worthwhile for users to take the risk of installing unfamiliar equipment. The definition of substantial savings undoubtedly varies depending on the user group, its level of sophistication, education, financial position, and willingness to take risks. It may mean that new systems would have to be as much as 10 to 30 percent cheaper in terms of unit costs to be appealing. Even so, to many users the promise of future savings (even in the near future) is not enough to offset the obvious appeal of a system like a diesel pump set that has a low initial cost.

10.6 Financing Water Systems

Inadequate financing has been a major contributing factor to the untimely failure of many water systems in developing countries. Besides using the LCC calculations to evaluate pumping system options, they can also be used to help assess a community's ability to pay for their water system. The success of water projects often depends upon who finances them. Often, financing for different cost components (capital or recurrent cost) comes from different sources. In many developing countries, governments or donor agencies pay for at least the installed capital cost of a system. Depending on the willingness and ability of a community to pay, governments or donor agencies may also pay part or all of the recurrent costs. Nonetheless, experience has shown that where beneficiary communities provide at least some of the financing, the likelihood of system sustainability increases accordingly.

As discussed throughout this manual, different systems have different capital as well as different recurrent costs. If communities are expected to pay some or all of these costs, it is best that they are fully aware of the magnitude of the costs when deciding on what type of system to install. During the system design phase, there should be full cost disclosure to all responsible parties (government agencies, donors, NGOs, and communities) so that everyone is aware of the size of the responsibility they are expected to bear.

The LCC technique presented in this chapter can be used to determine the size of water tariffs for a community water system. If you do this, however, **all system costs** must be included in the analysis (including the cost of the borehole or well development). External subsidies (if they are available) can be subtracted. The remainder is what should be charged to water consumers if full cost recovery is planned. Full cost recovery should include the cost of unforeseen events such as a complete failure of a major component (e.g., engine, well, or pipeline). Collecting water fees which are an extra 5-10% above what is strictly necessary for expected O&M costs normally poses a negligible additional burden on communities. It does, however, allow a community water committee's savings account to grow large enough (after several years of regular, conscientious, and equitable collection) to cover what might otherwise be financially disastrous situations (such as the catastrophic failure of a water storage tank, or the failure of a borehole which requires drilling a new one).

When users are given realistic estimates of the actual costs of a proposed water system, they are also much more likely to carefully evaluate the need for possibly over-designed (and costly) systems. For example, better awareness of real system cost would help to address initial reluctance to use handpumps, versus an otherwise preferred (but costlier) diesel pump with distributed taps. Also, if external financial support is available to cover the installed capital cost but not recurrent costs, users may be more likely to request a system with high capital cost and low recurrent costs (say a windmill or a solar pump), rather than the other way around (a diesel).

Once a system is chosen and installed, regular collection and proper management of user fees will be critical to system sustainability. Most communities need to be given training in financial management[6]. Community water committees are a common arrangement for developing community-based management capability. Besides organizational training, these committees should be given financial management training, focusing on simple bookkeeping procedures. Careful records must be kept on income (mainly water user fees) and all expenses (fuel, parts, labor) associated with the system. Not only is this important financially, but psychologically as well. Willingness to pay for water is in part based on the community's perception that their money is being responsibly managed to keep the water system operating properly, and not being diverted for unauthorized purposes.

So that people can be assured that their money is well spent, record books need to be clear and simple. There are many cases[7] where funds have been diverted (or even where people merely *thought* they were being diverted), causing people to stop paying fees and in turn causing systems to fail financially. As part of the system turn-over upon completion of installation, provide communities with proper account books and fee collection cards[8] (where fees are collected on a monthly basis, rather than by a flat fee for a certain sized container) and instruct them in their use. Encourage communities to collect fees on some kind of regular basis (e.g., by the container when water is collected, on a flat monthly basis, or after each harvest) so that they have money to pay for repairs when it is

6 For further discussion on community-level financial management, see *Rehabilitating Rural Water Systems - Planning and Implementation*, WASH Technical Report Series.

7 We have seen instances of this in certain rural water supply projects on Lombok and Sumbawa Islands in Indonesia, as well as in Sudan and Yemen. In some cases, funds were diverted for personal use. People found out about it, and subsequently refused to pay any more fees. In other cases, funds were diverted to support community activities other than the water system which benefitted only certain groups within the community, and not others. Non-beneficiaries then refused to pay their water fees. In both cases, systems failed due to lack of financial support.

8 Fee collection cards are like savings account passbooks. They indicate when a family has paid their monthly or annual water fee, and how much it was.

needed. While some communities or individuals may prefer to wait until the money is absolutely needed to pay their share, this is not recommended. For example, if a major breakdown occurs just before a harvest, a farming community may have no disposable income to cover the cost. It is much better practice to plan for such an eventuality in advance.

10.7 Summary of Pump Selection Procedures

This manual has taken you through the essential steps involved in properly selecting a pumping system for a small-scale, rural water supply. Its underlying assumption is that the use of equipment which is already locally available (ar so supportable) should be the first strategy considered in most cases. It is most likely that the stems commonly found in your area can be serviced locally and thus meet the most critical requirement for ensuring successful long-term operation.

In summary, the approach to pump selection described here is to:

- Calculate the pumping requirement (water demand and head), including expected demand growth over the system's useful lifetime.
- Determine what kind of equipment is available to meet these requirements.
- Review the local O&M infrastructure to see which types of equipment already can be supported, and which would require additional training of support personnel.
- Determine which kinds of available and supportable equipment meet your site requirements and can be supported over the long term.
- Calculate how much the remaining viable equipment options will cost to use.
- Based on life-cycle cost calculations and decisions about who is willing and able to pay particular costs, discuss the costs with all responsible groups (government water agencies, donors, NGOs, and, most importantly, the communities that will use the systems).
- Select the system option whose cost, technical, and O&M characteristics best fit the needs of the community or agency that will be using it.

While the technical requirements for a pumping system must obviously be met, remember that skilled labor, the availability of fuel and spare parts, good transportation facilities, and the importance of planning for future cash outlays needed to keep the system operating properly are also very important factors in selecting a sustainable pumping system.

We hope that this manual has clarified the procedures for determining these requirements and for comparing costs, thus assisting you to make a well-informed choice of a pumping system and components. However, the method given in this manual has necessarily been oversimplified in some ways. There are additional tools available to assist you in selecting a pumping system. Reviewing the annotated bibliography (Appendix A) will give you some insight into areas of further interest. There are also computer programs available that are relatively easy to use and can facilitate certain parts of the method presented here, especially the financial and economic analysis. Finally, remember that additional assistance with pump selection and comparative analysis is available through activities funded by international donors, such as the WASH Project, and a variety of institutions and private firms.

Appendix A: Annotated Bibliography

Arlosoroff, S., et al. *Community Water Supply: The Handpump Option.* Washington, DC: UNDP and World Bank, 1987.

Most recent comprehensive work published by the World Bank handpump development program. An excellent reference manual for policymakers and professionals on technical, social, and economic aspects of handpump use.

Asian Development Bank and United Nations Development Programme. *Women and Water: Domestic Shallow Well Water Supplies. The Family Handpump Scenario.* Proceedings of Regional Seminar: Manila, Philippines, 29 August-1 September 1989.

Bhatia, R. *Energy Alternatives for Irrigation Pumping: An Economic Analysis for Northern India.* World Employment Plan Research. Geneva, Switzerland: International Labor Organization, December 1984.

Economic evaluation of PV, grid-electric, diesel, bio-gas, dual-fuel, and windmills as energy sources for irrigation water pumping. Good discussion of potential role of rural electrification in remote-site irrigation pumping.

CIDA, DGIS, GTZ, USAID, and FAO. *Handbook for Comparative Evaluation of Technical and Economic Performance of Water Pumping Systems.* Ameersfoort, Netherlands: Consultancy Services Wind Energy Developing Countries (CWD), March 1987. (Draft.)

Detailed methodology for pump testing as well as technical, institutional, and socioeconomic evaluation of diesel, wind, solar PV, grid-electric, hand, and animal-traction pumps.

Driscoll, F. G., et al. *Groundwater and Wells.* St. Paul, Minnesota: Johnson Well Company, 1986.

Excellent technical reference on all important aspects of groundwater development, including aquifers; well hydraulics; designing, drilling, and developing wells (boreholes); pump selection and maintenance; and water quality and treatment.

Fraenkel, P. *Water-Lifting Devices.* FAO Irrigation and Drainage Paper. Rome, Italy: Food and Agriculture Organization of the United Nations, 1986.

Very comprehensive descriptions of the entire range of pumping and water-lifting devices used around the world. Gives operating characteristics and system design criteria for pumps and prime movers. Includes brief discussion of equipment selection.

Fraenkel, P. *The Power Guide: A Catalogue of Small-Scale Power Equipment.* Croton-on-Hudson, New York: Intermediate Technology Publications, 1979.

Excellent summary of power equipment costs, capacities, and descriptions, including solar, wind, water, biomass and thermal energy, internal and external combustion engines, and electrical generators, as well as instrumentation, monitoring, and control equipment. Somewhat dated on certain topics.

Hackleman, M. *Waterworks: An Owner/Builder Guide to Rural Water Systems.* Garden City, New Jersey: Dolphin Books, Doubleday and Company, 1983.

Good practical reference on domestic water system design and construction, with useful sections on options for hardware and system configurations.

Helvig, O.; Scott, V.; and Scalmanini, J. *Improving Well and Pump Efficiency.* Denver, Colorado: American Water Works Association, 1984.

Stresses efficiency concepts in water system design. Contains detailed practical strategies for improving the efficiency of wells and water pumping systems.

Hodgkin, J.; McGowan, R.; and White, R. *Small-Scale Water Pumping in Botswana.* Burlington, Vermont: Associates in Rural Development, Inc., (ARD) 1988. Five volumes--*I: Comparisons, II: Diesel Systems, III: Windmills, IV: Solar Pumps, and V: Other Pumping Technologies.*

Summarizes results of comparative pump testing program in Botswana that conducted field-testing and evaluation of a wide variety of pumps. Detailed technical, socio-institutional, and financial/economic analysis of pumping system alternatives.

Hodgkin, J.; McGowan, R.; Siddiq Adam Omer; Ali Abdelrahman Hamza; Ali Omer Eltayeb; and Nourella Yassin Ahmed. *Meeting Rural Pumping Needs in Sudan: An Analysis of Pumping System Choice (Diesel, Wind, or Solar).* Burlington, Vermont: Associates in Rural Development, Inc. (ARD), April 1991.

Summarizes detailed technical issues and related financial/economic concerns surrounding wind pump use, based on field tests conducted during Sudan Renewable Project (SREP).

Hofkes, E. H., and Visscher, J. T. *Renewable Energy Sources for Rural Water Supplies.* Technical Paper 23. The Hague, Netherlands: International Reference Centre for Community Water Supply and Sanitation (IRC), 1986.

Very useful general-purpose reference on basics of water pumping using solar, wind, hydropower, and biomass energy devices.

International Reference Center for Community Water Supply and Sanitation (IRC). *Maintenance Systems for Rural Water Supplies.* Occasional Paper No. 8. The Hague, Netherlands: IRC, 1975.

International Reference Center for Community Water Supply and Sanitation (IRC). *Practical Solutions in Drinking Water Supply and Wastes Disposal for Developing Countries.* Technical Paper No. 20. The Hague, Netherlands: IRC, February 1977.

Brief summary of low-cost, small-scale water collection, treatment, transportation, and distribution techniques as well as wastewater and solid waste disposal for developing countries. Good sections on simple, but effective, water filtration and chemical treatment devices, and their construction.

International Reference Center for Community Water Supply and Sanitation (IRC). *What Price Water? User Participation in Paying for Community-Based Water Supply.* Occasional Paper No. 10. The Hague, Netherlands: IRC, 1975.

Jordan, J. and Wyatt, A. *Estimating Operations and Maintenance Costs for Water Supply Systems in Developing Countries (WASH Technical Report #48).* January 1989.

Covers methods for estimating rural water supply O&M costs, including those for labor, materials, chemicals, utilities, transport, private contractors, and others.

Kenna, J., and Gillett, B. *Solar Water Pumping: A Handbook.* London, England: Intermediate Technology Publications, Ltd., 1985.

Good reference on solar pump operation and system sizing. Gives methodology for choosing PV systems based on technical selection criteria.

Kennedy, W. K., and Rogers, T. A. *Human- and Animal-Powered Water-Lifting Devices: A State-of-the-Art Survey.* London, England: Intermediate Technology Publications, Ltd., 1985.

Discusses "state of the art" for human- (now slightly dated) and animal-powered pumps, including past and ongoing performance studies in developing countries. Suggests potential applications and areas where further research is warranted.

Lancashire, S.; Kenna, J.; and Fraenkel, P. *Windpumping Handbook.* London, England: Intermediate Technology Publications, Ltd., 1987.

Good practical reference on wind-pumping technology, including sizing for water supply and irrigation, and information on procurement, installation, and maintenance.

Lysen, E. H. *Introduction to Wind Energy.* 2nd ed. Ameersfoort, Netherlands: Steering Committee Wind Energy in Developing Countries (SWD, now CWD), May 1983.

Very detailed general reference on design and theory of operation for electrical and mechanical wind machines, with an emphasis on water-pumping applications.

McGowan, R.; Hodgkin, J.; Kaplan, P.; and Waldstein, A. *Rehabilitating Rural Water Systems: Planning and Implementation.* Burlington, Vermont: Associates in Rural Development, Inc. (ARD), January 1992.

Summarizes technical and socioeconomic issues involved with rural water system rehabilitation researched under the Water and Sanitation for Health Project.

Oelert, G; Auer, F.; and Pertz, K. *Economic Issues of Renewable Energy Systems, A Guide to Project Planning (Second Corrected Edition).* Eschborn, 1988.

Discusses the energy and economic situations in developing countries, and analyzes performance and costs for various renewable energy applications (including wind and solar pumping) to determine their viability compared to conventional energy sources.

Okun, D., and Ernst, W. *Community Piped Water Supply Systems in Developing Countries.* World Bank Technical Paper No. 60. Washington, DC: World Bank, 1987.

Provides checklists for identifying sites and projects and planning and designing community piped water supplies. Useful coverage of system design process, with general focus on most relevant technical issues and good discussion of infrastructural support/planning requirements.

Sandia National Laboratory, *Stand Alone Photovoltaic Systems, A Handbook of Recommended Design Practices.* Photovoltaic Design Assistance Center, SNL, Albuquerque, November 1988.

Summarizes design and life cycle costing procedures for a variety of PV applications, including lighting, refrigeration, water pumping, and others.

Stewart, H. *Pumps.* Indianapolis, Indiana: T. Audel & Co., 1982.

Technical treatment of operating principles, design, operation, maintenance, and repair of many common types of pumps. Aimed at helping technicians understand nuts-and-bolts operating principles.

U.S. Environmental Protection Agency (EPA). *Manual of Individual Water Supply Systems.* EPA-430/9-74-007. Washington, DC: EPA Office of Water Programs, Water Supply Division, 1975.

Deals with ground water and well development, surface water sources, water treatment, pumping, distribution, and storage for domestic water supplies.

Water Systems Council. *Water Systems Handbook.* 8th ed. Chicago, Illinois: Water Systems Council, 1983.

A practical guide to water system design with emphasis on electrical and mechanical aspects of domestic water supplies, including sections on troubleshooting and repairs.

World Bank. *Village Water Supply.* Washington, DC: World Bank, March 1976.

Good brief summary of all aspects of village drinking-water supply projects. Covers technical aspects, costs (in summary fashion), financial aspects, organization and management, justifying investments, policy issues, and project and program design.

World Health Organization. *Preventive Maintenance of Rural Water Supplies.* November 1984.

Gives detailed maintenance schedules for diesel, gravity, and handpump systems.

Appendix B: Friction Losses*

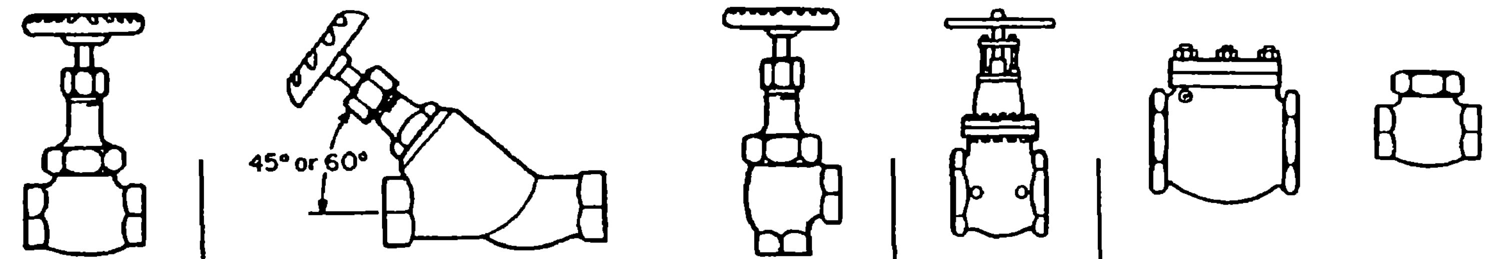
*Information in this Appendix was taken from:

Theodore Baumeister, Euguene A. Avallone, and Theodore Baumeister, III (eds.), *Marks' Standard Handbook for Mechanical Engineers*, 8th ed. (New York,: McGraw-Hill Book Company), pp. 12-106 and 12-109.

and

Flow of Fluids through Valves, Fittings, and Pipe. Technical Paper No. 410M, The Crane Company, New York, 1980.

Appendix B1:
Valve Losses in Equivalent Feet and Meters of Pipe for Screwed, Welded, Flanged, and Flared Connections



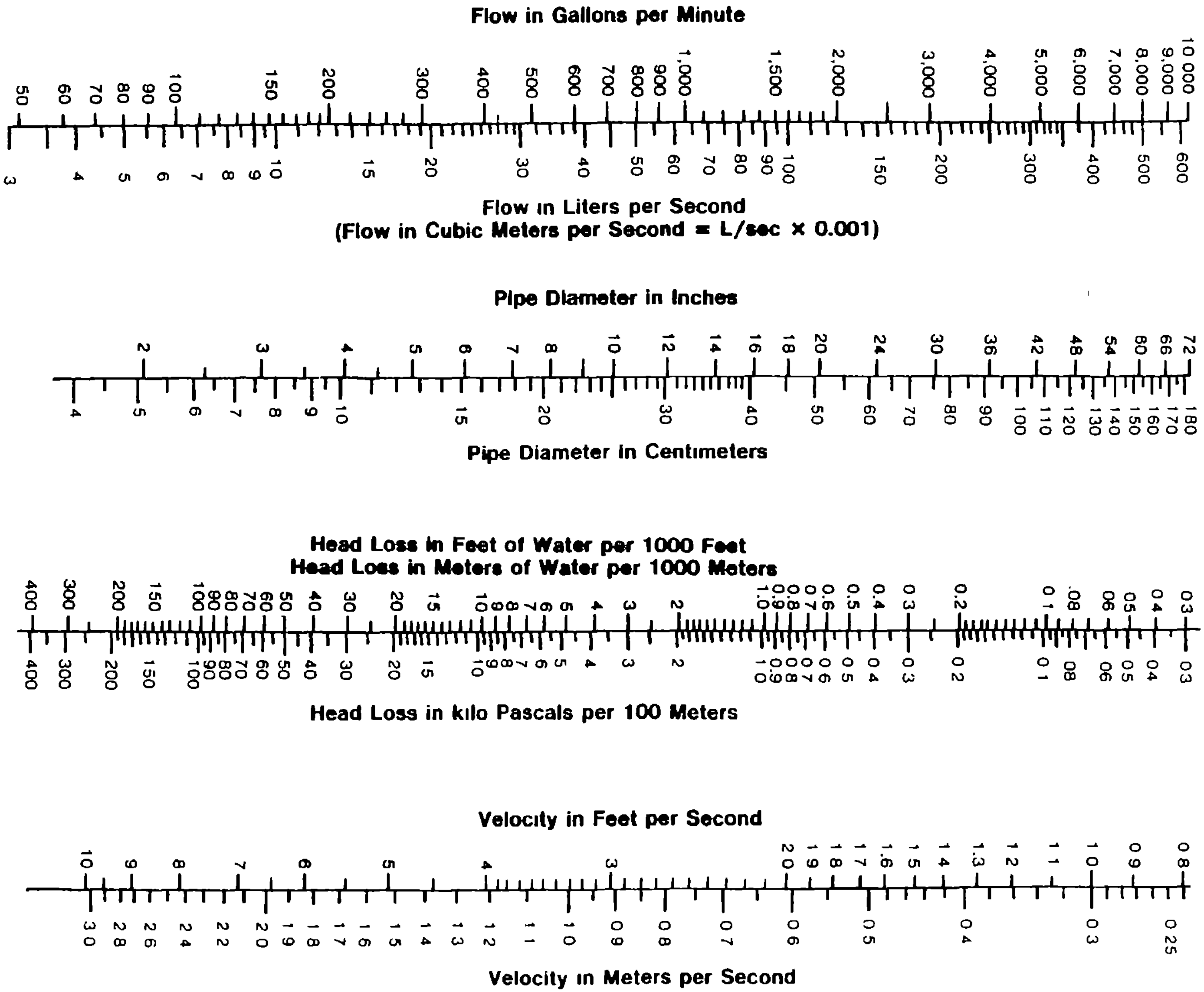
Nominal pipe or tube size		Globe†		60° Y		45° Y		Angle†		Gate‡		Swing check§		Lift check
in	mm	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	
3/8	10	17	5.0	8	2.4	6	1.8	6	1.8	0.6	0.2	5	1.5	
1/2	12	18	5.5	9	2.7	7	2.1	7	2.1	0.7	0.2	6	1.8	
3/4	20	22	6.7	11	3.4	9	2.7	9	2.7	0.9	0.3	8	2.4	Globe and
1	25	29	8.8	15	4.6	12	3.7	12	3.7	1.0	0.3	10	3.0	vertical
1¼	32	38	11.6	20	6.1	15	4.6	15	4.6	1.5	0.5	14	4.3	lift
1½	40	43	13.1	24	7.3	18	5.5	18	5.5	1.8	0.5	16	4.9	same as
2	50	55	16.8	30	9.1	24	7.3	24	7.3	2.3	0.7	20	6.1	globe
2½	60	69	21.0	35	10.7	29	8.8	29	8.8	2.8	0.9	25	7.6	valve¶
3	80	84	25.6	43	13.1	35	10.7	35	10.7	3.2	1.0	30	9.1	
3½	90	100	30.5	50	15.2	41	12.5	41	12.5	4.0	1.2	35	10.7	
4	100	120	36.6	58	17.7	47	14.3	47	14.3	4.5	1.4	40	12.2	
5	130	140	42.7	71	21.6	58	17.7	58	17.7	6	1.8	50	15.2	
6	150	170	51.8	88	26.8	70	21.3	70	21.3	7	2.1	60	18.3	
8	200	220	67.1	115	35.1	85	25.9	85	25.9	9	2.7	80	24.4	
10	250	280	85.3	145	44.2	105	32.0	105	32.0	12	3.7	100	30.5	
12	300	320	97.5	165	50.3	130	39.6	130	39.6	13	4.0	120	36.6	Angle lift
14	350	360	109.7	185	56.4	155	47.2	155	47.2	15	4.6	135	41.1	same as
16	400	410	125.0	210	64.0	180	54.9	180	54.9	17	5.0	150	45.7	angle
18	450	460	140.2	240	73.2	200	61.0	200	61.0	19	5.8	165	50.3	valve
20	500	520	158.5	275	83.8	235	71.6	235	71.6	22	6.7	200	61.0	
24	600	610	185.9	320	97.5	265	80.8	265	80.8	25	7.6	240	73.2	

*Losses are for all valves in fully open position.
†These losses do not apply to valves with needlepoint-type seats.
‡Regular and short pattern plug cock valves, when fully open, have same loss as gate valve. For valve losses of short-pattern plug cocks above 6 in, check manufacturer.
§Losses also apply to the in-line, ball-type check valve.
¶For Y pattern globe lift-check valve with seat approximately equal to the nominal pipe diameter, use values of 60° Y valve for loss.

Appendix B2: Galvanized Iron Pipe Losses

PIPE FLOW CHART
English/Metric Units

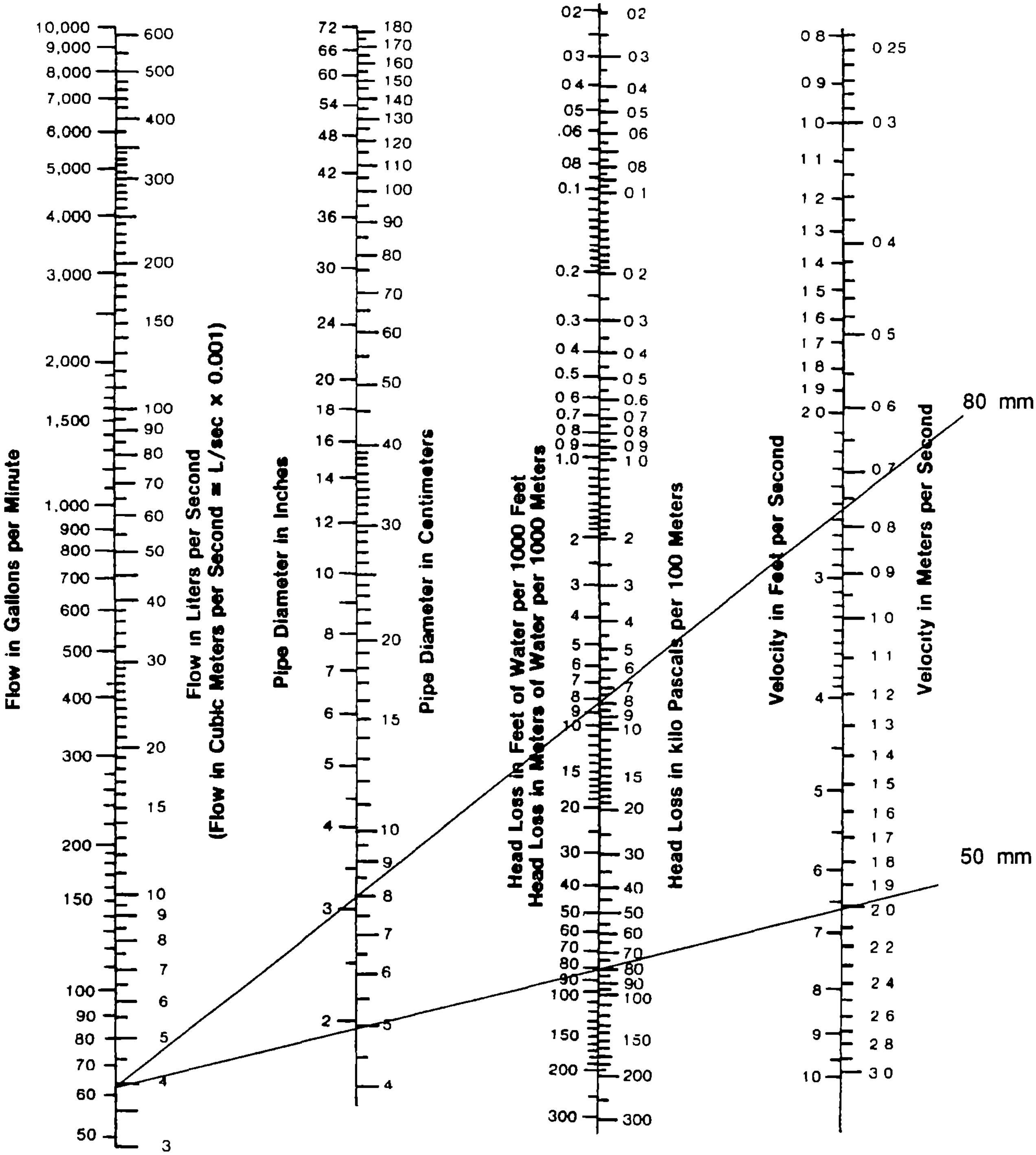
Source: Mueller Co., Decatur, Ill.



Appendix B3: Plastic Pipe Losses

Source: Mueller Co., Decatur, Ill.

PIPE FLOW CHART
English/Metric Units



Appendix B4: Iron Pipe Dimensions

Selected from ISO 336 - 1974 and BS 3600 : 1973

Nominal Pipe Size (Inches)	Outside Diameter (mm)	Thickness (mm)	Inside Diameter (mm)
1/8	10.2	1.6	7.0
		1.8	6.6
		2.0	6.2
		2.3	5.6
1/4	13.5	1.8	9.9
		2.0	9.5
		2.3	8.9
		2.6	8.3
		2.9	7.7
3/8	17.2	2.0	13.2
		2.3	12.6
		2.6	12.0
		2.9	11.4
		3.2	10.8
1/2	21.3	2.6	16.1
		2.9	15.5
		3.2	14.9
		3.6	14.1
		4.0	13.3
		4.5	12.3
		5.0	11.3
		5.4	10.5
3/4	26.9	2.6	21.7
		2.9	21.1
		3.2	20.5
		3.6	19.7
		4.0	18.9
		4.5	17.9
		5.0	16.9
		5.4	16.1
		5.6	15.7
		5.9	15.1
		6.3	14.3
		7.1	12.7
1	33.7	3.2	27.3
		3.6	26.5
		4.0	25.7
		4.5	24.7
		5.0	23.7
		5.4	22.9
		5.6	22.5
		5.9	21.9
		6.3	21.1
		7.1	19.5
		8.0	17.7
		8.8	16.1
1¼	42.4	3.2	36.0
		3.6	35.2
		4.0	34.4
		4.5	33.4
		5.0	32.4
		5.4	31.6
		5.6	31.2
		5.9	30.6
		6.3	29.8
		7.1	28.2
		8.0	26.4
		8.8	24.8
		10.0	22.4*
1½	48.3	3.2	41.9
		3.6	41.1
		4.0	40.3
		4.5	39.3
		5.0	38.3
		5.4	37.5
		5.6	37.1
		5.9	36.5
		6.3	35.7
		7.1	34.1
		8.0	32.3
		8.8	30.7
		10.0	28.3
2	60.3	3.6	53.1
		4.0	52.3
		4.5	51.0
		5.0	50.3
		5.4	49.5
		5.6	49.1
		5.9	48.5
		6.3	47.7
		7.1	46.1
		8.0	44.3
		8.8	42.7
		10.0	40.3
		11.0	38.3
2½	76.1	5.0	66.1
		5.4	65.3
		5.6	64.9
		5.9	64.3
		6.3	63.5
		7.1	61.9
		8.0	60.1
		8.8	58.5
		10.0	56.1
		11.0	54.1
		12.5	51.1
		14.2	47.7
3	88.9	5.4	78.1
		5.6	77.7
		5.9	77.1
		6.3	76.3
		7.1	74.7
		8.0	72.9
		8.8	71.3
		10.0	68.9
		11.0	66.9
		12.5	63.9
		14.2	60.5
		16.0	56.9
3½	101.6	5.6	90.4
		5.9	89.8
		6.3	89.0
		7.1	87.4
		8.0	85.6
		8.8	84.0
		10.0	81.6
		11.0	79.6
		12.5	76.6
		14.2	73.2
		16.0	69.6
		17.5	66.6
4	114.3	5.6	103.1
		5.9	102.5
		6.3	101.7
		7.1	100.1
		8.0	98.3
		8.8	96.7
		10.0	94.3
		11.0	92.3
		12.5	89.3
		14.2	85.9
		16.0	82.3
		17.5	79.3
		20.0	74.3
5	139.7	5.9	127.9
		6.3	127.1
		7.1	125.5
		8.0	123.7
		8.8	122.1
		10.0	119.7
		11.0	117.7
		12.5	114.7
		14.2	111.3
		16.0	107.7
		17.5	104.7
		20.0	99.7

* Not included in BS 3600 : 1973

—The Crane Company

Appendix C: Typical Recommended Service for Diesel Engines

The following summarizes the recommended service intervals for Lister engines. The engine model is given in parentheses (e.g., ST, LT, 8/1). Where no model is specified, the procedure applies to all.

Daily	Check supply of diesel fuel and oil level Check air filter (in dusty conditions)
125 hrs	Check air filter (in moderately dusty conditions, renew if necessary) Check for oil and fuel leaks Check and tighten nuts and bolts as necessary Clean engine and mounting
250 hrs	Change engine oil Clean the restrictor banjo union in the lubricating oil feed line Renew oil filter if fitted (ST) Clean injector nozzle if exhaust is dirty Renew fuel filter if necessary Check belt tension
500 hrs	Decarbonize if necessary (LT) Renew fuel filter element (ST) Adjust valve clearances (LT) Change oil in oil bath air filters (8/1 so equipped)
1000 hrs	Decarbonize (8/1) and if necessary (ST) Change filter elements (8/1) Adjust valve clearances (LT)
1500 hrs	Decarbonize (LT) Examine and clean fan blades (LT) Check governor linkage and adjustment (LT) Drain and clean fuel tank (LT) Renew fuel filter (LT) Clean and test the injector nozzle (LT) Check fuel pump timing (LT) Check oil pump and its valves (LT) Renew the air filter element (LT)
2000 hrs	Decarbonize (ST) Clean inlet and exhaust system (ST) Examine and clean fan blades (ST) Check governor linkage and adjustment (ST) Drain and clean fuel tank (ST) Renew fuel filter (ST) Clean and test the injector nozzle (ST) Check fuel pump and its valves (ST) Renew the air filter element (ST)

Appendix D: Handpump Selection Tables*

* Arlosoroff et al. 1987, 80-87

GUIDE TO PUMP SELECTION TABLES

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The discharge rate deemed "adequate" for each pumping lift is noted at the top of the appropriate table The rate reduces as depth increases, for the reasons explained in Box 5 1 Some deepwell pumps thus achieve lower ratings for low-lift applications, where users will opt for pumps giving greater discharges A special note is made where a pump is available with a range of cylinder sizes or adjustable stroke length, to suit different depths

Column 4 — Ease of Maintenance

Ratings indicate the ease with which maintenance can be carried out by:

- A — A village caretaker
- B — An area mechanic
- C — A mobile maintenance team

Column 5 — Reliability

Reliability ratings are an indication of the proportion of the time that the pump is likely to be functioning properly Separate ratings are given for different daily outputs. The ratings combine judgments of the "mean time before failure" (MTBF) and the probable "downtime" when the pump is waiting to be repaired They thus take account of the fact that pumps which are suitable for village maintenance and can be repaired quickly may be more "reliable" than those which require more complex maintenance, even if the latter break down less frequently

Column 6 — Corrosion Resistance

Ratings are based primarily on the materials of the downhole components Galvanized steel pumprods and rising mains are not corrosion resistant in aggressive water and earn a — rating

Column 7 — Abrasion Resistance

Ratings indicate the pump's capability to pump sand-laden water Performance in laboratory and field trials is combined with assessment of the seal and valve types For non-suction pumps, leather cups seals are rated — , though the extent of abrasion damage will be related to the daily output of the pump Analysts may therefore accept lower rated pumps for light duty applications

Column 8 — Manufacturing Needs

Ratings indicate the ease with which a pump could be manufactured in a developing country with the specified level of industrial development.

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The Analyst develops a short list by entering a check mark against those pumps meeting his selection criteria

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Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation.

Notes 9 and 10. The India Mark II uses a gravity return on the plunger, and requires a minimum cylinder setting of 24 meters (one manufacturer offers a fixed-link system for shallower settings)

Note 14. The Maldev is a pumphead only All ratings are based on the use of conventional downhole components

Note 16. Reliability ratings for the Monolift are based on pumps with metal gears. Plastic gears were less reliable

Note 21. The **oo** corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion

Note 23. The **oo** discharge rating for the Volanta takes account of the pump's adjustable stroke length Present designs require a minimum well diameter of 110mm

Note 30. Downhole components of the Kangaroo are corrosion resistant The **o** rating relates to the pedal return spring

Note 40. The Rower is designed as an irrigation pump, and has a high discharge It is widely used for domestic water supply in Bangladesh

Table S.1

Maximum pumping lift — 7 meters
"Adequate" discharge rate — 19 liters/minute

1	2	3	4			5			6	7	8			9	10	11
	Data	Discharge	Ease of maintenance			Reliability for (m^3/d)			Corr	Abr	Manufacturing needs			Short	Price	
Pump name	source	rate	A	B	C	1.5	4	8	res.	res	1	2	3	list	(US$)	Remarks
HIGH LIFT PUMPS (0-45 meters)																
1 Abi-ASM	L (F)	—	—	oo	oo	oo	o	—	oo	o	—	o	o			**See Note 1**
2 Afridev	(F)	o	oo	oo	oo	oo	oo	o	o	o	o	oo	oo			**See Note 2**
3 AID Deriv Deepwell	L F	oo	—	oo	oo	oo	o	—	—	—	—	oo	oo			
4 Bestobell	L	o	—	oo	oo	oo	o	—	o	o	o	oo	oo			
5 Climax	L	oo*	—	—	oo	oo	oo	o	—	—	—	—	oo			
6 Dragon 2	L	o	—	oo	oo	oo	o	—	—	—	—	o	oo			
7 Duba Tropic 7	F	oo*	—	o	oo	oo	o	—	—	—	—	—	oo			**See Note 7**
8 GSW	L (F)	o*	—	oo	oo	oo	oo	o	—	—	—	o	oo			
9 India Mark II (standard)	L F	o	—	oo	oo	oo	oo	oo	—	—	—	o	oo			**See Note 9**
10 India Mark II (modified)	(F)	o	—	oo	oo	oo	oo	oo	—	o	—	o	oo			**See Note 10**
~~11 Jetmatic Deepwell~~	L	o	—	oo	oo	oo	oo	o	—	—	—	o	oo			
~~12 Kardia~~	L (F)	o	—	oo	oo	oo	oo	o	oo	o	—	o	oo			
13 Korat	L F	oo*	—	oo	oo	oo	oo	o	—	—	—	oo	oo			
14 Maldev	L F	oo*	—	oo	oo	oo	oo	o	—	—	o	oo	oo			**See Note 14**
15 Monarch P3	L F	oo*	—	oo	oo	oo	oo	o	—	—	—	o	oo			
16 Monolift	L (F)	—	—	—	oo	oo	oo	o	—	oo	—	—	oo			**See Note 16**
17 Moyno	L F	—	—	—	oo	oo	oo	o	—	oo	—	—	o			
18 Nira AF84	L	o	—	oo	oo	oo	oo	o	oo	o	—	o	oo			
19 Philippines Deepset	(F)	o	—	oo	oo	oo	o	—	—	—	o	oo	oo			
20 SWN 80 & 81	F	oo*	—	oo	oo	oo	oo	oo	oo	oo	—	oo	oo			
~~21 Vergnet~~	L F	—	o	oo	oo	oo	oo	o	oo	o	—	o	o			**See Note 21**
22 VEW A18	L	o	—	o	oo	oo	o	—	oo	—	—	—	o			
23 Volanta	L F	oo	o	oo	oo	oo	oo	oo	oo	oo	o	o	oo			**See Note 23**
INTERMEDIATE LIFT PUMPS (0-25 meters)																
24 Consallen LD6	L F	oo*	—	oo	oo	oo	oo	o	oo	o	—	o	oo			
25 DMR (Dempster deriv.)	F	oo*	—	oo	oo	oo	o	—	—	—	—	oo	oo			
26 Nira AF76	L F	oo*	—	oo	oo	oo	o	—	—	o	—	oo	oo			
LOW LIFT PUMPS (0-12 meters)																
27 Blair	F	o	oo	oo	oo	oo	o	—	oo	o	o	oo	oo			
28 Ethiopia BP50	L	oo	o	oo	oo	oo	o	o	o	—	o	oo	oo			**7m max. lift**
29 IDRC-UM	L	oo	o	oo	oo	oo	o	—	oo	—	o	oo	oo			
30 Kangaroo	L F	oo	—	oo	oo	oo	o	—	o	oo	—	o	oo			**See Note 30**
31 Malawi Mark V	F	oo	o	oo	oo	o	—	—	oo	o	o	oo	oo			**7m max. lift**
32 Nira AF85	L F	oo	oo	oo	oo	oo	oo	oo	oo	o	o	oo	oo			
33 Tara	L F	oo	oo	oo	oo	oo	o	—	o	—	o	oo	oo			
SUCTION PUMPS (0-7 meters)																
34 AID Suction	F	oo	o	oo	oo	oo	o	—	—	o	—	oo	oo			
35 Bandung	L	oo	oo	oo	oo	oo	oo	o	o	o	—	oo	oo			
36 Inalsa Suction	F	oo	o	oo	oo	oo	o	—	—	—	—	oo	oo			
37 Jetmatic Suction	(F)	oo	o	oo	oo	oo	o	—	o	o	—	oo	oo			
38 Lucky	F	oo	o	oo	oo	o	—	—	—	o	—	oo	oo			
39 New No 6	L (F)	oo	oo	oo	oo	oo	o	—	—	oo	—	oo	oo			
40 Rower	L (F)	oo	oo	oo	oo	oo	oo	o	o	o	oo	oo	oo			**See Note 40**
41 SYB-100	F	oo	o	oo	oo	oo	oo	o	o	oo	—	oo	oo			
42 Wasp	F	oo	o	oo	oo	oo	o	—	—	o	—	oo	oo			
ADDITIONAL PUMPS																
A1																
A2																
A3																
A4																

* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

GUIDE TO PUMP SELECTION TABLES

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Ratings are based primarily on the materials of the downhole comp[o]nents. Galvanized steel pumprods and rising mains are not corrosi[on] resistant in aggressive water and earn a — rating

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Ratings indicate the pump's capability to pump sand-laden water. Performance in laboratory and field trials is combined with assessment of the seal and valve types Leather cupseals are rated — , though t[he] extent of abrasion damage will be related to the daily output of the pum[p] Analysts may therefore accept lower rated pumps for light duty applications

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Special features of individual pumps are noted in this colu[mn] Amplification of the notes is given below

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Notes 9 and 10. The India Mark II uses a gravity return on the plunger, and requires a minimum cylinder setting of 24 meters (one manufacturer offers a fixed-link system for shallower settings).

Note 14. The Maldev is a pumphead only All ratings are based on the use of conventional downhole components

Note 16. Reliability ratings for the Monolift are based on pumps w[ith] metal gears Plastic gears were less reliable.

Note 21. The **oo** corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion

Note 23. The **oo** discharge rating for the Volanta takes account of t[he] pump's adjustable stroke length Present designs require a minimum w[ell] diameter of 110mm

Note 30. Downhole components of the Kangaroo are corrosion resistant. The **o** rating relates to the pedal return spring

Table S.2

Maximum pumping lift — 12 meters
"Adequate" discharge rate — 16 liters/minute

1	2	3	4			5			6	7	8			9	10	11
			Ease of maintenance			Reliability for (m^3/d)					Manufacturing needs					
Pump name	Data source	Discharge rate	A	B	C	1 5	4	8	Corr res.	Abr res	1	2	3	Short list	Price (US$)	Remarks
HIGH LIFT PUMPS (0-45 meters)																
1 Abi-ASM	L (F)	o	—	oo	oo	oo	o	—	oo	o	—	o	o			**See Note 1**
2 Afridev	(F)	oo	oo	oo	oo	oo	oo	o	o	o	o	oo	oo			**See Note 2**
3 AID Deriv Deepwell	L F	oo	—	oo	oo	oo	o	—	—	—	—	oo	oo			
4 Bestobell	L	o	—	oo	oo	oo	o	—	o	o	o	oo	oo			
5 Climax	L	oo*	—	—	oo	oo	oo	o	—	—	—	—	oo			
6 Dragon 2	L	o	—	oo	oo	oo	o	—	—	—	—	o	oo			
7 Duba Tropic 7	F	oo*	—	o	oo	oo	o	—	—	—	—	—	oo			**See Note 7**
8 GSW	L (F)	o*	—	oo	oo	oo	oo	o	—	—	—	o	oo			
9 India Mark II (standard)	L F	o	—	oo	oo	oo	oo	oo	—	—	—	o	oo			**See Note 9**
10 India Mark II (modified)	(F)	o	—	oo	oo	oo	oo	oo	—	o	—	o	oo			**See Note 10**
11 Jetmatic Deepwell	L	o	—	oo	oo	oo	oo	o	—	—	—	o	oo			
12 Kardia	L (F)	o	—	oo	oo	oo	oo	o	oo	o	—	o	oo			
13 Korat	L F	oo*	—	oo	oo	oo	oo	o	—	—	—	oo	oo			
14 Maldev	L F	oo*	—	oo	oo	oo	oo	o	—	—	o	oo	oo			**See Note 14**
15 Monarch P3	L F	oo*	—	oo	oo	oo	oo	o	—	—	—	o	oo			
16 Monolift	L (F)	o	—	—	oo	oo	oo	o	—	oo	—	—	oo			**See Note 16**
17 Moyno	L F	—	—	—	oo	oo	oo	o	—	oo	—	—	o			
18 Nira AF84	L	o	—	oo	oo	oo	oo	o	oo	o	—	o	oo			
19 Philippines Deepset	(F)	o	—	oo	oo	oo	o	—	—	—	o	oo	oo			
20 SWN 80 & 81	F	oo*	—	oo	oo	oo	oo	oo	oo	oo	—	oo	oo			
21 Vergnet	L F	—	o	oo	oo	oo	oo	o	oo	o	—	o	o			**See Note 21**
22 VEW A18	L	o	—	o	oo	oo	o	—	oo	—	—	—	o			
23 Volanta	L F	oo	o	oo	oo	oo	oo	oo	oo	oo	o	o	oo			**See Note 23**
INTERMEDIATE LIFT PUMPS (0-25 meters)																
24 Consallen LD6	L F	oo*	—	oo	oo	oo	o	—	oo	o	—	o	oo			
25 DMR (Dempster deriv)	F	oo*	—	oo	oo	oo	o	—	—	—	—	oo	oo			
26 Nira AF76	L F	oo*	—	oo	oo	oo	o	—	—	o	—	oo	oo			
LOW LIFT PUMPS (0-12 meters)																
27 Blair	F	o	oo	oo	oo	oo	o	—	oo	o	o	oo	oo			
28 Ethiopia BP50	L															**7m max. lift**
29 IDRC-UM	L	oo	o	oo	oo	oo	o	—	oo	—	o	oo	oo			
30 Kangaroo	L F	oo	—	oo	oo	oo	o	—	o	oo	—	o	oo			**See Note 30**
31 Malawi Mark V	F															**7m max. lift**
32 Nira AF85	L F	oo	oo	oo	oo	oo	oo	o	oo	o	o	oo	oo			
33 Tara	L F	oo	oo	oo	oo	o	—	—	o	—	o	oo	oo			
ADDITIONAL PUMPS																
A1																
A2																
A3																
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* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer

GUIDE TO PUMP SELECTION TABLES

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Special features of individual pumps are noted in this column Amplification of the notes is given below.

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Table S.3

Maximum pumping lift — 25 meters

"Adequate" discharge rate — 10 liters/minute

1	2	3	4			5		6	7	8			9	10	11
			Ease of maintenance			*Reliability for (m³/d)*				*Manufacturing needs*					
Pump name	*Data source*	*Discharge rate*	*A*	*B*	*C*	*4*	*8*	*Corr res*	*Abr res*	*1*	*2*	*3*	*Short list*	*Price (US$)*	*Remarks*
HIGH LIFT PUMPS (0-45 meters)															
1 Abi-ASM	L (F)	o	—	oo	oo	o	—	oo	o	—	o	o			**See Note 1**
2 Afridev	(F)	oo	oo	oo	oo	oo	o	o	o	o	oo	oo			**See Note 2**
3 AID Denv Deepwell	L F	o	—	o	oo	—	—	—	—	—	oo	oo			
4 Bestobell	L	o	—	o	oo	o	—	o	o	o	oo	oo			
5 Climax	L	oo*	—	—	oo	oo	o	—	—	—	—	oo			
6 Dragon 2	L	o	—	o	oo	—	—	—	—	—	o	oo			
7 Duba Tropic 7	F	oo*	—	o	oo	o	—	—	—	—	—	oo			**See Note 7**
8 GSW	L (F)	oo*	—	o	oo	o	—	—	—	—	o	oo			
9 India Mark II (standard)	L F	oo	—	o	oo	o	—	—	—	—	o	oo			
10 India Mark II (modified)	(F)	oo	—	oo	oo	oo	o	—	o	—	o	oo			
11 Jetmatic Deepwell	L	o	—	o	oo	—	—	—	—	—	o	oo			
12 Kardia	L (F)	oo	—	oo	oo	o	—	oo	o	—	o	oo			
13 Korat	L F	oo*	—	o	oo	o	—	—	—	—	oo	oo			
14 Maldev	L F	oo*	—	o	oo	o	—	—	—	o	oo	oo			**See Note 14**
15 Monarch P3*	L F	oo	—	o	oo	o	—	—	—	—	o	oo			
16 Monolift	L (F)	o	—	—	oo	oo	o	—	oo	—	—	oo			**See Note 16**
17 Moyno	L F	o	—	—	oo	oo	o	—	oo	—	—	o			
18 Nira AF84	L	o	—	o	oo	oo	o	oo	o	—	o	oo			
19 Philippines Deepset	(F)	oo	—	o	oo	o	—	—	—	o	oo	oo			
20 SWN 80 & 81	F	oo*	—	o	oo	o	—	oo	oo	—	oo	oo			
21 Vergnet	L F	o	o	oo	oo	oo	o	oo	o	—	o	o			**See Note 21**
22 VEW A18	L	o	—	—	oo	o	—	oo	—	—	—	o			
23 Volanta	L F	oo	o	oo	oo	oo	oo	oo	oo	o	o	oo			**See Note 23**
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A1															
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- C — A mobile maintenance team

Column 5 — Reliability

Reliability ratings are an indication of the proportion of the time that the pump is likely to be functioning properly. Separate ratings are given for different daily outputs The ratings combine judgments of the "mean time before failure" (MTBF) and the probable "downtime" when the pump is waiting to be repaired. They thus take account of the fact that pump which are suitable for village maintenance and can be repaired quickl may be more "reliable" than those which require more co le maintenance, even if the latter break down less frequently

Column 6 — Corrosion Resistance

Ratings are based primarily on the materials of the downhole c pc nents Galvanized steel pumprods and rising mains are not cor io resistant in aggressive water and earn a — rating

Column 7 — Abrasion Resistance

Ratings indicate the pump's capability to pump sand-laden wate Performance in laboratory and field trials is combined with asses er of the seal and valve types. Leather cupseals are rated — , thou th extent of abrasion damage will be related to the daily output of the m Analysts may therefore accept lower rated pumps for light dut applications

Column 8 — Manufacturing Needs

Ratings indicate the ease with which a pump could be manufactured in developing country with the specified level of industrial development

- 1 — Low industrial base, limited quality control
- 2 — Medium-level industry, no special processes
- 3 — Advanced industry, good quality control

Column 9 — Short List

The Analyst develops a short list by entering a check mark again: those pumps meeting his selection criteria.

Column 10 — Capital Cost

Analysts should obtain current prices for short-listed pumps

Column 11 — Remarks

Special features of individual pumps are noted in this c mr Amplification of the notes is given below

Amplification of the ratings for individual pumps can be found in the Handpump Compendium

NOTES ON TABLES

The notes relate to pumps with the same reference number — i.e Note 14 refers to Pump 14, the Maldev In the tables, ratings to which the note refers are highlighted [o]

Note 1. The **oo** corrosion rating for the Abi-ASM is based on current models Earlier models did suffer from corrosion.

Note 2. The **o** corrosion rating for the Afridev is based on the use of stainless steel pumprods, offered as an option

Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation

Note 12. The manufacturer recommends a maximum depth of 4 meters for the Kardia

Note 14. The Maldev is a pumphead only All ratings are based th use of conventional downhole components

Note 16. Reliability ratings for the Monolift are based on pumps wi metal gears Plastic gears were less reliable A 2 1 gear ratio is suppli for deepwell applications

Note 21. The **oo** corrosion rating for the Vergnet is based on rer models Earlier models did suffer from corrosion

Note 23. The **oo** discharge rating for the Volanta takes account of th pump's adjustable stroke length Present designs require a minimu we diameter of 110mm.

Table S.4

Maximum pumping lift — 45 meters
"Adequate" discharge rate — 7 liters/minute

1	2	3	4			5	6	7	8			9	10	11
			Ease of maintenance			*Reliability for (m³/d)*			*Manufacturing needs*					
Pump name	*Data source*	*Discharge rate*	*A*	*B*	*C*	*4*	*Corr res.*	*Abr. res*	*1*	*2*	*3*	*Short list*	*Price (US$)*	*Remarks*
HIGH LIFT PUMPS (0-45 meters)														
1 Abi-ASM	L (F)	o	—	oo	oo	—	oo	o	—	o	o			See Note 1
2 Afridev	(F)	oo	oo	oo	oo	o	o	o	o	oo	oo			See Note 2
3 AID Denv. Deepwell	L F	o	—	o	oo	—	—	—	—	oo	oo			
4 Bestobell	L	o	—	o	oo	—	o	o	o	oo	oo			
5 Climax	L	oo*	—	—	oo	o	—	—	—	—	oo			
6 Dragon 2	L	o	—	o	oo	—	—	—	—	o	oo			
7 Duba Tropic 7	F	oo*	—	o	oo	—	—	—	—	—	oo			See Note 7
8 GSW	L (F)	oo*	—	o	oo	—	—	—	—	o	oo			
9 India Mark II (standard)	L F	oo	—	o	oo	—	—	—	—	o	oo			
10 India Mark II (modified)	(F)	oo	—	oo	oo	o	—	o	—	o	oo			
11 Jetmatic Deepwell	L	oo	—	o	oo	—	—	—	—	o	oo			
12 Kardia	L (F)	oo	—	o	oo	—	oo	o	—	o	oo			See Note 12
13 Korat	L F	oo*	—	o	oo	—	—	—	—	oo	oo			
14 Maldev	L F	oo*	—	o	oo	—	—	—	o	oo	oo			See Note 14
15 Monarch P3	L F	oo*	—	o	oo	—	—	—	—	o	oo			
16 Monolift	L (F)	o	—	—	oo	o	—	oo	—	—	oo			See Note 16
17 Moyno	L F	o	—	—	oo	o	—	oo	—	—	o			
18 Nira AF84	L	o	—	o	oo	o	oo	o	—	o	oo			
19 Philippines Deepset	(F)	oo	—	o	oo	—	—	—	o	oo	oo			
20 SWN 80 & 81	F	oo*	—	o	oo	—	oo	oo	—	oo	oo			
21 Vergnet	L F	o	o	oo	oo	o	oo	o	—	o	o			See Note 21
22 VEW A18	L	o	—	—	oo	—	oo	—	—	—	o			
23 Volanta	L F	oo	o	oo	oo	o	oo	oo	o	o	oo			See Note 23
ADDITIONAL PUMPS														
A1														
A2														
A3														
A4														

* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

Appendix E: Checklist for Materials, Labor, and Transportation

This appendix contains a checklist of materials, labor, and transportation. It can be used to ensure that all items have been considered in the technical and economic analysis.

Diesel

pump
pump head
shafts
pipe engine
clutch
shaft
extension
pulley
belts
pressure relief
water meter
non-return (backflow) valve
hose tap
union
gate valve
pipe and fittings (elbows, nipples, couplings, etc.)
cement
sand
gravel
reinforcing mesh
engine
frame
foundation bolts
lock for pump house
fuel storage tank
labor: skilled supervisory and mechanic
semiskilled pipefitters, mechanic helpers
unskilled labor
labor per diem allowances
transportation

Delivery pipe network

- pipe
- elbows, tees, and connections
- gate valves
- unions
- labor: skilled supervisory
  - semiskilled tank installers, pipefitters
  - unskilled labor
- labor per diem allowances
- transportation

Distribution pipe network

- pipe (more than one size?)
- elbows, tees, and connections
- distribution boxes and valve chambers
- shut-offs and gate valves
- standpipes and taps
- labor: skilled supervisory
  - semiskilled tank installers, pipefitters
  - unskilled labor
- labor per diem allowances
- transportation

Storage tank

- storage tank
- tank stand
- tank liner
- water level indicator
- inflow and outflow connections
- overflow and drain connections
- pipe from borehole to tank
- labor: skilled supervisory
  - semiskilled tank installers, pipefitters
  - unskilled labor
- labor per diem allowances
- transportation

Solar pumps

modules
array support structures
wiring connections
foundation bolts
array foundation
grounding rod
controller
batteries
battery storage and protection
pump
pump motor
submersible pump cable
safety wire
borehole clamp
sand
gravel
cement
labor: supervisory, skilled electrician
semiskilled pipefitters, electrician helpers
unskilled labor
labor per diem allowances
transportation

Windmills

windmill head
tower
pump cylinder
piping
pumprod
sand
gravel
cement
clamp of forcehead
fence (gate, wire corner posts, regular posts, barbed wire?)
labor: skilled supervisory
semiskilled pipefitters, installers
unskilled labor
labor per diem allowances
transportation

Handpumps

- pump head
- pump
- piping
- pump (sucker) rods
- cement
- rebar for well cap
- sand
- gravel
- labor: skilled supervisory
  - semiskilled or unskilled labor
- labor per diem allowances
- transportation

Annual costs

- financing charges for capital costs
- pump operator
- fuel and oil
- consumables (cleaning materials, etc.)
- spares: maintenance (filters, belts, etc.)
- spares: repair (pumpset, pipelines, storage)
- labor: skilled mechanic/electrician
  - semiskilled pipefitters
  - unskilled muscle
- labor per diem allowances
- transportation (no. of trips)

Non-annual costs

- pump replacement
- engine replacement
- module replacement (damage or theft)
- controller replacement
- battery replacement
- tank replacement
- rebuild well/redrill borehole

Appendix F: Formulas Used in Present Worth Analysis

Compound Interest Rate Factors

(Based on Annual Compounding)

F1 = Factor Used to Calculate the Present Worth of a Single Future Payment
F2 = Factor Used to Calculate the Present Worth of a Uniform Series of Future Payments

Discount Rate (in %, compounded annually)

Nmbr.of	6.00%		8.00%		10.00%		12.00%		15.00%	
Years (N)	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
1	0.9434	0.9434	0.9259	0.9259	0.9091	0.9091	0.8929	0.8929	0.8696	0.8696
2	0.8900	1.8334	0.8573	1.7833	0.8264	1.7355	0.7972	1.6901	0.7561	1.6257
3	0.8396	2.6730	0.7938	2.5771	0.7513	2.4869	0.7118	2.4018	0.6575	2.2832
4	0.7921	3.4651	0.7350	3.3121	0.6830	3.1699	0.6355	3.0373	0.5718	2.8550
5	0 7473	4.2124	0.6806	3.9927	0.6209	3.7908	0.5674	3.6048	0.4972	3.3522
6	0.7050	4.9173	0.6302	4.6229	0.5645	4.3553	0.5066	4.1114	0.4323	3.7845
7	0.6651	5.5824	0.5835	5.2064	0.5132	4.8684	0.4523	4.5638	0.3759	4.1604
8	0.6274	6.2098	0.5403	5.7466	0.4665	5.3349	0.4039	4.9676	0.3269	4.4873
9	0.5919	6.8017	0.5002	6.2469	0.4241	5.7590	0.3606	5.3282	0.2843	4.7716
10	0.5584	7.3601	0.4632	6.7101	0.3855	6.1446	0.3220	5.6502	0.2472	5.0188
11	0.5268	7.8869	0.4289	7.1390	0.3505	6.4951	0.2875	5.9377	0.2149	5.2337
12	0.4970	8.3838	0.3971	7.5361	0.3186	6.8137	0.2567	6.1944	0.1869	5.4206
13	0 4688	8.8527	0.3677	7.9038	0.2897	7.1034	0.2292	6.4235	0.1625	5.5831
14	0.4423	9.2950	0.3405	8.2442	0.2633	7.3667	0.2046	6.6282	0.1413	5.7245
15	0.4173	9.7122	0.3152	8.5595	0.2394	7.6061	0.1827	6.8109	0.1229	5.8474
16	0.3936	10.1059	0.2919	8.8514	0.2176	7.8237	0.1631	6.9740	0.1069	5.9542
17	0.3714	10.4773	0.2703	9.1216	0.1978	8.0216	0.1456	7.1196	0.0929	6.0472
18	0.3503	10.8276	0.2502	9.3719	0.1799	8.2014	0.1300	7.2497	0.0808	6.1280
19	0.3305	11.1581	0.2317	9.6036	0.1635	8.3649	0.1161	7.3658	0.0703	6.1982
20	0.3118	11.4699	0.2145	9.8181	0.1486	8.5136	0.1037	7.4694	0.0611	6.2593

Note: The use of the factors given in the table above is explained in detail in Chapter Ten.

Appendix G: Estimating Solar Radiation on Tilted PV Arrays

Determining the correct value for the amount of solar radiation that will fall upon a PV array is an inexact science. Solar radiation varies not only over the day, the month, and the year, but also on the angle of the surface upon which it is intercepted. Nonetheless, some estimate of radiation levels must be made for solar pump design purposes. The spreadsheet given on the following page shows how this is done.

Solar radiation has two components, direct beam (directly from the sun) and diffuse (the portion of incoming extraterrestrial radiation which is diffused by water vapor and other gases in the atmosphere, and so lights up the sky). To calculate how much total radiation is intercepted by a tilted array on the ground, you must calculate both the amount of direct beam and the amount of diffuse radiation which falls upon the array. The spreadsheet on the following page is based on the Page Correlation, which correlates the percentage of total horizontal solar radiation which is diffuse (F_d) with what is called the monthly average clearness index (K_t). K_t can be calculated by dividing the monthly values for total solar radiation on a horizontal surface on the ground (H, which is often recorded at meteorological stations around the world) by the monthly values for the average daily extraterrestrial radiation on a horizontal surface (H_o). H is measured by weather instruments at a particular location, and is dependent upon local latitude and weather. H_o depends upon several variables including the day of the year for the average day of a particular month (n), the sunset hour angle[1], and the declination of the Earth (delta), and the latitude (phi).

H_o for each month of the year is calculated in Table One of the spreadsheet for latitudes between 30 degrees North and 30 degrees South of the Equator[2]. Next, known measured solar data (H) for a particular site in Sudan are given. Dividing H by H_o gives the monthly average clearness ratio K_t. Then using the Page Correlation, the percentage of the total horizontal solar radiation (H) which is diffuse (F_d) is then:

$$F_d = 1 - 1.13 * K_t$$

The percentage of H which is direct beam radiation (F_b) is then:

$$F_b = 1 - F_d$$

To find the total radiation intercepted by a tilted surface such as a PV array, you have to first calculate the portion of H which is direct beam by multiplying H by F_b, and then calculate the portion of H which is diffuse by multiplying H by F_d. The total radiation on the tilted array can then be calculated by multiplying the direct beam component by a Tilt Factor (given in the accompanying

[1]Using the formula: $\cos \omega_s = -\frac{\sin \varphi \sin \delta}{\cos \varphi \cos \delta} = -\tan \varphi \tan \delta$

[2]Using the formula: $H_o = \frac{24 \times 3600 G_{sc}}{\pi} \left(1 + 0.033 \cos \frac{360n}{365}\right) \times \left(\cos \varphi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \varphi \sin \delta\right)$

Tables[3], and based on latitude and the tilt angle of the array), and adding the diffuse component multiplied by a similar geometric factor related only to the tilt angle of the array, which is:

Diffuse Radiation on a Tilted Surface = $H * F_d * \{1+(\cos \beta)/2\}$

where β (beta) is the tilt angle of the array. The results of these calculations are shown for three different tilt angles at the bottom of the spreadsheet. Since the amount of useable solar radiation can usually be optimized by tilting the array at an angle up from the horizontal equal to the latitude plus 5-10 degrees, only Tilt Factor tables for those ranges are given here. This analysis assumes that you have sited your array so that it points within 5-10 degrees of due South (North of the Equator) or due North (South of the Equator). Readers interested in finding out more about estimating solar radiation levels are encouraged to read the reference previously given.

Calculating Solar Radiation on Tilted PV Arrays

Table 1: Calculating Daily Extraterrestrial Radiation on a Horizontal Surface

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Phi	Delta=	-20.9	-13.0	-2.4	9.4	18.8	23.1	21.2	13.5	2.2	-9.6	-18.9	-23.0
(Lat.)	n=	17	47	75	105	135	162	198	228	258	288	318	344
-30		43.0	39.5	34.1	27.2	21.4	18.7	19.8	24.5	31.1	37.5	41.9	43.7
-25		42.5	39.9	35.4	29.4	24.1	21.5	22.5	26.9	32.8	38.2	41.7	43.0
-20		41.8	40.0	36.5	31.4	26.6	24.2	25.1	29.1	34.2	38.6	41.1	42.1
-15		40.8	39.8	37.3	33.1	28.9	26.8	27.6	31.1	35.4	38.7	40.4	40.8
-10		39.5	39.3	37.8	34.6	31.1	29.2	29.9	32.9	36.3	38.5	39.3	39.4
-5		38.0	38.5	38.0	35.8	33.0	31.4	32.0	34.4	36.9	38.1	38.0	37.6
0		36.2	37.5	37.9	36.8	34.8	33.5	33.9	35.7	37.2	37.4	36.4	35.7
5		34.2	36.1	37.5	37.5	36.3	35.4	35.6	36.7	37.3	36.4	34.6	33.5
10		32.0	34.6	36.9	37.9	37.5	37.0	37.1	37.5	37.1	35.1	32.5	31.1
15		29.6	32.7	36.0	38.1	38.6	38.4	38.3	38.0	36.6	33.6	30.2	28.5
20		26.9	30.7	34.8	37.9	39.3	39.5	39.3	38.3	35.8	31.8	27.8	25.8
25		24.2	28.4	33.3	37.5	39.8	40.5	40.0	38.2	34.7	29.8	25.1	22.9
30		21.3	25.9	31.6	36.8	40.0	41.1	40.5	37.9	33.4	27.6	22.3	19.9

Fraction of Radiation which is diffuse is F(d) = 1-1.13*K(t) by the Page Correlation, where K(t) = H/H(o).

For Dongola (Sudan), monthly average horizontal solar radiation levels (MJ/square meter per day) are:

H =	20.2	23.0	25.6	27.0	27.7	27.4	25.9	25.2	24.1	23.0	20.9	19.1

Now calculate K(t) = H/H(o). Since the solar radiation data are only for one site (at 20 Degrees North Latitude), K(t) only need be calculated for that particular Latitude. Use H from the previous line, and H(o) from the table just above that, calculating K(t) = H/H(o) gives:

(Latitude)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
20	0.75	0.75	0.74	0.71	0.71	0.69	0.66	0.66	0.67	0.72	0.75	0.74

[3] From *Solar Engineering of Thermal Processes, 2nd Edition*, John Duffie and William Beckman, John Wiley and Sons, 1991.

Calculate the fraction which is diffuse F(d) from the monthly K(t) values above, where: F(d) = 1-1.13*K(t)

0.15	0.15	0.17	0.20	0.20	0.22	0.25	0.26	0.24	0.18	0.15	0.16

Subtracting out the F(d) to get percentage of H(o) which is direct beam, or F(b) = H(o)-F(d) gives:

0.85	0.85	0.83	0.80	0.80	0.78	0.75	0.74	0.76	0.82	0.85	0.84

To get Total Radiation on the Tilted Surface, add diffuse and beam. Calculate the diffuse and direct beam components separately, then add them together. To calculate direct beam, use the appropriate Tilt Factor given in the accompanying tables, where Ŀ (phi) is the latitude of the site, and ß (beta) is the tilt angle of the PV array from the horizontal. To calculate the diffuse component, multiply the monthly H value given above for Dongola by the monthly F(b) times {1+(cos ß)/2}:

Table 2: Total Radiation on a Tilted Surface at Latitude=20 Degrees North
(For Various Array Tilt Angles)

Tilt Angle=	20		(phi-beta = 20-20 = 0)									
Tilt Factor=	1.33	1.22	1.09	0.97	0.88	0.84	0.86	0.93	1.04	1.17	1.30	1.37
Dir. Beam	22.7	23.9	23.1	21.1	19.4	18.0	16.6	17.4	19.1	22.1	23.1	21.9
Diffuse	4.6	5.1	6.4	7.8	8.3	8.8	9.7	9.5	8.4	6.1	4.6	4.6
Total Tilt	27.2	29.0	29.5	28.8	27.7	26.7	26.3	26.9	27.6	28.2	27.7	26.5
								Annual Average Monthly=				27.7
Tilt Angle=	25		(phi-beta = 20-25 = -5)									
Tilt Factor=	1.39	1.25	1.09	0.94	0.84	0.80	0.98	0.90	1.03	1.20	1.35	1.44
Dir. Beam	23.7	24.4	23.1	20.4	18.6	17.1	19.0	16.9	18.9	22.6	24.0	23.0
Diffuse	4.5	5.1	6.3	7.7	8.2	8.7	9.6	9.4	8.3	6.1	4.6	4.5
Total Tilt	28.2	29.5	29.4	28.1	26.7	25.8	28.6	26.3	27.3	28.7	28.5	27.5
								Annual Average Monthly=				27.4
Tilt Angle=	30		(phi-beta = 20-30 = -10)									
Tilt Factor=	1.44	1.27	1.09	0.91	0.79	0.74	0.76	0.86	1.01	1.21	1.39	1.49
Dir. Beam	24.5	24.8	23.1	19.8	17.5	15.8	14.7	16.1	18.6	22.8	24.7	23.8
Diffuse	4.5	5.1	6.3	7.7	8.2	8.7	9.6	9.4	8.3	6.1	4.6	4.5
Total Tilt	29.1	29.9	29.4	27.4	25.6	24.5	24.3	25.5	26.9	28.9	29.2	28.3
								Annual Average Monthly=				26.7

Table D-7 $\phi - \beta = 0^{\circ}$

ϕ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.06	1.04	1.01	0.98	0.96	0.95	0.95	0.97	1.00	1.03	1.05	1.06
10	1.13	1.08	1.03	0.97	0.92	0.90	0.91	0.95	1.00	1.06	1.12	1.14
15	1.22	1.14	1.05	0.97	0.90	0.87	0.88	0.94	1.02	1.11	1.20	1.24
20	1.33	1.22	1.09	0.97	0.88	0.84	0.86	0.93	1.04	1.17	1.30	1.37
25	1.48	1.31	1.14	0.98	0.86	0.81	0.83	0.93	1.07	1.25	1.43	1.53
30	1.66	1.43	1.20	1.00	0.85	0.79	0.82	0.93	1.12	1.35	1.60	1.74
35	1.91	1.59	1.28	1.02	0.85	0.77	0.80	0.94	1.17	1.48	1.82	2.02
40	2.26	1.79	1.38	1.05	0.84	0.75	0.79	0.96	1.24	1.64	2.12	2.42
45	2.76	2.07	1.51	1.09	0.83	0.73	0.77	0.98	1.33	1.86	2.55	3.02
50	3.55	2.46	1.69	1.15	0.83	0.69	0.75	1.00	1.45	2.17	3.21	4.00
55	4.94	3.06	1.92	1.21	0.81	0.64	0.72	1.03	1.60	2.60	4.30	5.86
60	7.96	4.04	2.25	1.28	0.77	0.55	0.65	1.05	1.80	3.28	6.45	10.50
ϕ	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun

Table D-8 $\phi - \beta = -5^{\circ}$

ϕ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.05	1.03	1.00	0.97	0.95	0.94	0.94	0.96	0.99	1.02	1.04	1.05
5	1.11	1.06	1.01	0.96	0.91	0.89	0.90	0.94	0.99	1.05	1.10	1.12
10	1.18	1.11	1.03	0.94	0.88	0.85	0.86	0.92	1.00	1.08	1.16	1.20
15	1.28	1.17	1.06	0.94	0.86	0.82	0.84	0.90	1.01	1.13	1.25	1.31
20	1.39	1.25	1.09	0.94	0.84	0.80	0.82	0.90	1.03	1.20	1.35	1.44
25	1.54	1.34	1.14	0.96	0.83	0.78	0.80	0.90	1.06	1.27	1.49	1.60
30	1.73	1.47	1.20	0.97	0.83	0.76	0.79	0.91	1.11	1.37	1.66	1.82
35	1.99	1.63	1.28	1.00	0.83	0.76	0.79	0.92	1.16	1.50	1.89	2.11
40	2.35	1.83	1.38	1.03	0.83	0.75	0.79	0.94	1.23	1.67	2.20	2.53
45	2.87	2.12	1.51	1.08	0.84	0.75	0.79	0.97	1.32	1.89	2.64	3.15
50	3.68	2.52	1.69	1.14	0.86	0.76	0.80	1.01	1.44	2.20	3.31	4.17
55	5.12	3.13	1.92	1.21	0.88	0.76	0.81	1.05	1.59	2.65	4.44	6.09
60	8.23	4.12	2.25	1.30	0.90	0.77	0.82	1.11	1.79	3.33	6.65	10.89
ϕ	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun

Table D-9 $\phi - \beta = -10^{\circ}$

ϕ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.09	1.05	1.00	0.94	0.89	0.87	0.88	0.92	0.97	1.03	1.08	1.10
5	1.15	1.08	1.01	0.92	0.86	0.83	0.84	0.89	0.97	1.06	1.13	1.17
10	1.23	1.13	1.02	0.91	0.83	0.79	0.81	0.88	0.98	1.10	1.20	1.25
15	1.32	1.19	1.05	0.91	0.81	0.76	0.78	0.86	0.99	1.15	1.29	1.36
20	1.44	1.27	1.09	0.91	0.79	0.74	0.76	0.86	1.01	1.21	1.39	1.49
25	1.59	1.37	1.13	0.92	0.78	0.72	0.75	0.86	1.05	1.29	1.53	1.66
30	1.79	1.49	1.20	0.94	0.78	0.71	0.74	0.87	1.09	1.39	1.71	1.89
35	2.05	1.65	1.27	0.97	0.78	0.70	0.74	0.88	1.14	1.52	1.94	2.19
40	2.42	1.86	1.38	1.00	0.78	0.70	0.74	0.90	1.21	1.69	2.26	2.62
45	2.95	2.15	1.51	1.04	0.79	0.70	0.74	0.93	1.30	1.91	2.71	3.26
50	3.79	2.56	1.68	1.10	0.81	0.70	0.75	0.96	1.41	2.22	3.40	4.30
55	5.26	3.17	1.91	1.17	0.83	0.71	0.76	1.01	1.56	2.67	4.55	6.27
60	8.43	4.18	2.24	1.26	0.85	0.71	0.77	1.06	1.76	3.36	6.80	11.19
ϕ	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun

WATER AND SANITATION
FOR HEALTH PROJECT
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Sponsored by the U.S. Agency
for International Development

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7 August 1992

TAS 223

Dear Colleague:

On behalf of the WASH Project, I am pleased to provide you with a copy of **WASH Technical Report No. 61, Pump Selection: A Field Guide for Energy Efficient and Cost Effective Water Pumping Systems for Developing Countries.** The manual was written by Richard McGowan and Jonathon Hodgkin. This manual is an updated version of an earlier "Pump Selection" report dated January 1989. The revisions are based on field trials and experiences carried out during the intervening years.

Many handbooks have been written on the subject of rural water supply, irrigation, and pump selection. Until recently, most of these focused primarily on the technical skills and spare parts, system reliability, ease of installation and/or operation, and related considerations that are important to users were discussed only briefly. This manual deals not only with these issues, but also with all other major issues which are important when considering the long-term sustainability of systems.

The purpose of this manual is to assist engineers, economists, managers, and designers in developing countries to select water pumping systems for rural and small scale peri-urban water users. It is intended to enable readers to better understand and evaluate the advantages and disadvantages of different types of pumping systems and their components (e.g., pumps, engines, and controls), associated costs, and long-term O&M requirements. With this information, readers can make knowledgeable, cost-effective choices of water pumping equipment, which will result in water development projects that are more effective and that offer increased water availability and minimize costs to users. While this manual focuses on pumps for potable water supplies, it can also be used to determine pumping equipment for small to medium scale agricultural use. This manual addresses four kinds of pumped water systems: diesel, wind, solar, and hand pumps. However, the methods can be applied easily to any kind of system (grid-electric, gasoline engines, etc.)

If you have any questions or comments about the findings or recommendations contained in this report, we will be happy to discuss them. Please contact Phil Roark at the WASH Operations Center. Please let us know if you would like additional copies.

Sincerely,

Craig Hafner
Acting Project Director

Enclosure

CH:kf

Camp Dresser & McKee International Inc.
Associates in Rural Development, Inc.
International Science and Technology Institute
Research Triangle Institute
University Research Corporation
Training Resources Group
University of North Carolina at Chapel Hill

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THE WASH PROJECT

With the launching of the United Nations International Drinking Water Supply and Sanitation Decade in 1979, the United States Agency for International Development (A I D) decided to augment and streamline its technical assistance capability in water and sanitation and in 1980, funded the Water and Sanitation for Health Project (WASH). The funding mechanism was a multi-year, multi-million dollar contract, secured through competitive bidding. The first WASH contract was awarded to a consortium of organizations headed by Camp Dresser & McKee International Inc. (CDM), an international consulting firm specializing in environmental engineering services. Through two other bid proceedings since then, CDM has continued as the prime contractor.

Working under the close direction of A.I.D.'s Bureau for Science and Technology, Office of Health, the WASH Project provides technical assistance to A I.D missions or bureaus, other U.S. agencies (such as the Peace Corps), host governments, and non-governmental organizations to provide a wide range of technical assistance that includes the design, implementation, and evaluation of water and sanitation projects, to troubleshoot on-going projects, and to assist in disaster relief operations WASH technical assistance is multi-disciplinary, drawing on experts in public health, training, financing, epidemiology, anthropology, management, engineering, community organization, environmental protection, and other subspecialties.

The WASH Information Center serves as a clearinghouse in water and sanitation, providing networking on guinea worm disease, rainwater harvesting, and peri-urban issues as well as technical information backstopping for most WASH assignments.

The WASH Project issues about thirty or forty reports a year WASH *Field Reports* relate to specific assignments in specific countries, they articulate the findings of the consultancy. The more widely applicable *Technical Reports* consist of guidelines or "how-to" manuals on topics such as pump selection, detailed training workshop designs, and state-of-the-art information on finance, community organization, and many other topics of vital interest to the water and sanitation sector In addition, WASH occasionally publishes special reports to synthesize the lessons it has learned from its wide field experience.

For more information about the WASH Project or to request a WASH report, contact the WASH Operations Center at the above address.